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PREFACE.

This book is intended for the general student. Accordingly I have avoided, as far as possible, symbolical reasoning of all kinds. Also, where the science has become an art, I have not pursued the subject into details, unless the art favourably illustrate the science.

Because the book is not a history of discovery, I have omitted men's names wherever I could.

The illustrations are not drawn to scale. They are of such proportion and simplicity as may best show principles.

Based upon the notes of the lectures which I have given during the last six years to mining students and science teachers, I hope the book may be useful to a larger public.

Frederick Guthrie.

London, *November 1875.*

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MAGNETISM AND ELECTRICITY.

BOOK I.

FRICTIONAL OR STATIC ELECTRICITY.

CHAPTER I.

ATTRACTION AND REPULSION.

1. There are certain substances which, after being rubbed by other substances, are found to have, and to retain for some time, the power of attracting and being attracted by every substance in its ordinary state. Such power of attraction is said to be due to electricity; the bodies rubbed are said to be electrified; to be electric; to be electrically excited, or simply to be excited.

2. During such development of electricity by friction, the bodies rubbed together need not be, and in many cases are not, sensibly rubbed away; so that the appearance of electricity under such circumstances may be compared to the appearance of heat by friction. There is, however, this notable distinction between the development of frictional heat and frictional electricity. Heat appears whenever two bodies, like or unlike, are rubbed together; and the quantity of heat produced is directly proportional to the labour employed (work done) in overcoming the friction. For the production of frictional electricity there must be some difference, constitutional (chemical), structural, or thermal, between the surfaces of the bodies rubbed together. An increase in the friction, and the work done in overcoming it, by no means cause an increase in the quantity of the electricity finally presented—often, indeed, the reverse. And, further, the same amount of labour being expended, the quantity of the electricity varies greatly with the nature of the substances used.

3. It seems that whenever any two unlike surfaces whatever are rubbed together, or brought into contact and separated, a certain quantity of electricity is manifested. But such generalization must necessarily depend upon analogy, extended from the observation of the immense number and variety of the instances in which electricity is thus produced, and generally supported by the fact that it may be matter of extreme difficulty to detect electricity in many cases.

4. With regard to the alternative in Art. 3, between rubbing and approach and withdrawal, it may be pointed out that rubbing is, in fact, the successive approach and withdrawal of the parts of the two bodies concerned. When one surface slides rectilineally over another, every point of each has been at least in contact with an entire line of the other, and not with only one point, as is the case when the two are simply put together and pulled apart without sliding.

5. Although, as above stated, electricity generally, perhaps universally, accompanies friction between unlike bodies, this universality has only been suspected, roughly speaking, within the last hundred years. It was at first supposed to be peculiar to amber (rubbed on the dry hand or wool), which substance has given its name to the science. The reason why the electrical condition of other rubbed bodies was overlooked is, because bodies having weight must have material support connecting them with the earth, and because the majority of substances, whether used as exciters of electricity or as supports for excited bodies, allow the electricity to travel freely over their surfaces and through their substance so nimbly that, after electrical excitement, they are presently again in the same state as the earth itself. In other words, the electricity escapes from them, over them, and through them, to the earth, and becomes thus quickly lost to all means of detection.

6. It becomes, therefore, essential, if we wish to examine *the electrical condition* of bodies, to find substances to serve

as their supports which do not allow, or only slowly allow, the electricity to pass through. Such substances are called non-conductors, or imperfect conductors; and a body, electrified or not, which is supported by such a substance, is said to be insulated or isolated. The subject of conduction will be specially studied in Arts. 18-20. But, even at starting, it will be well to bear in mind the few following facts, on account of their importance in the experiments shortly to be described. Water conducts frictional electricity with great readiness. The inappreciably thin film of water which covers most substances in the ordinary state of the air, is sufficient to connect electrically excited bodies supported on such substances with the earth, and so allow their electricity to escape. The solid substances most frequently used as isolators are glass, silk, shell-lac, sulphur, vulcanized caoutchouc, and ebonite, all of which must be strictly dry. Glass, when used as an isolator, is generally heated and covered with shell-lac varnish.* Resinous substances, such as shell-lac, do not condense moisture from the air, so that the glass surface is thus kept dry by contact with the shell-lac, and no film of water is formed upon the lac. Owing to this disturbing influence of the moisture of the air, all experiments in frictional electricity succeed best in frosty weather, when the air is at its dryest; and electrical apparatus should, in all cases before use, be warmed a few degrees above the atmospheric temperature. For this purpose they may be placed between a screen and a brisk open fire.

7. Attraction between an Electrified and an Unelectrified Body.—If we turn a round-bottomed two-ounce flask upside down, and put its neck into the neck of a wine bottle, and balance upon the round surface of the flask a wooden lath about three feet long, we have (fig. 1) an easy and excellent means of exhibiting electric attraction. Thus, a lump of amber, rubbed on warm flannel, and held near either end of the lath, will draw it round. The same effect is produced by bringing near to the lath a sheet of brown packing-paper, which, having been held before the fire till it is scorching hot, has been briskly brushed with a clothes brush of hogs' bristles; or by a strip of gutta-percha which has been drawn lightly between two dry fingers; or by a silk ribbon which has been drawn from end to end between two fingers armed with two pieces of vulcanized caoutchouc tubing; or by a sheet of thin writing paper which has been rubbed on a hot, dry board with a piece of bottle caoutchouc; or by a film of collodion* which has been drawn between the dry fingers; or by a warm, dry glass tube which has been rubbed with an amalgam of mercury, zinc, and tin,† spread upon a silk cushion; or by sealing-wax which has been rubbed with flannel; or by a stick of sulphur which has been rubbed with flannel. Further, the nature of the non-electrified body may be varied indefinitely. Thus, the electrified amber, brown paper, etc., attract fragments of gold leaf, bran, feathers, etc. The thin writing paper and silk ribbon may be so strongly electrified as to cling to the wall; while the glass tube, sulphur, and sealing-wax may become so strongly electric as to set in motion, from a distance of two or three inches, empty egg-shells, rolls of paper a foot in diameter, etc. In short, if any substance whatever, which is not electrified, be hung by a slender thread, it will be drawn out of the vertical by any of the above-mentioned substances when they are electrically excited; and this will occur whether the non-electrified body be electrically isolated or not; that is, it may be hung by silk thread, whereby it is isolated, or by a cotton one, whereby it forms, electrically speaking, a part of the earth.

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* See Appendix, I.

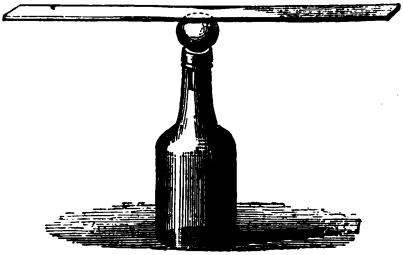

Fig. 1.

8. Attraction and Repulsion between Electrified Bodies.—In order to examine the mechanical behaviour of two electrified bodies towards one another, one of them must be free to move, and be supported by some isolating material. The latter condition is advantageous in all cases, and manifestly essential, if the electrified movable body be a conductor. If the electrified body held in the hand be a conductor, the hand must be furnished with a non-conducting material, such as a sheet of vulcanized caoutchouc. Simple and convenient forms of isolating supports are shown in figs. 2 and 3. In fig. 2 a bar of electrified matter is placed in a silk-covered wire stirrup, and hung by a thin silk tape. In fig. 3 a dry wine bottle, having its neck varnished with shell-lac, carries a cork, through which is thrust, point upwards, a darning needle. A little glass conical cap,* which is fastened

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* *See Appendix, II.* † See Appendix, III.

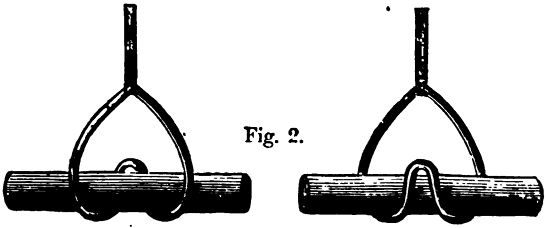
Fig. 2.

Fig. 4.

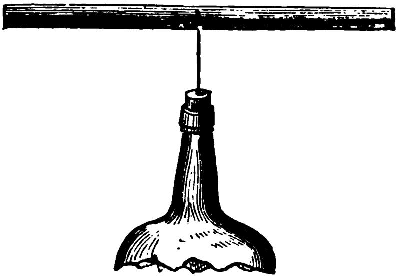
Fig. 3.

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* See Appendix, IV.

to the object balanced, rests upon the needle's point. If the balanced body be sulphur or wax, the glass cap can be thrust into it on the end of a thick, hot wire. If the substance be infusible, a hole is drilled through, and the cap is cemented on. If the balanced electrified body be glass, it may consist of a wide tube closed at both ends, and having an indentation in the middle to receive the needle point.*

9. In the experiments described in Art. 7, we observed that in all cases attraction ensued; and although there was a considerable difference in the amount of attraction exhibited by the various substances, yet we appeared to be dealing with the same force throughout. If now we rub a stick of sealing-wax with flannel, and place it on the stirrup, as in fig. 2, or on the needle-point, as in fig. 3, we find, of course, that either end of it is attracted by wood, feathers, egg-shells, our own bodies, sealing-wax, glass, and, in fact, by all non-electrified bodies. If, further, we bring near it a tube of glass which has been rubbed with amalgamed silk, we find that the two attract one another with greater force than if the glass had not been rubbed. Finally, if we bring near the excited wax another piece of wax similarly excited with flannel, we find the movable wax violently driven away, or *repelled.* Pursuing the experiment further, we find that sulphur when rubbed with flannel also repels sealing-wax rubbed with flannel. If we place excited glass in the stirrup, we shall find it to be attracted by all unelectrified bodies: to be still more strongly attracted by wax rubbed with flannel, but to be *repelled* by glass similarly excited to itself (by amalgam, on silk), and to be repelled by writing paper rubbed with caoutchouc. Hence it is generally concluded that the electricity of sealing-wax rubbed with flannel is of a different kind to that of the glass rubbed with the amalgamed silk; for the first attracts, the second repels, glass excited by amalgamed silk; and the first repels, and the second attracts, sealing-wax rubbed with flannel, thus:

Sealing-wax (rubbed with flannel) repels *Sealing-wax* (rubbed with flannel)

attracts attracts

Glass (rubbed with amalgamed silk) repels *Glass* (rubbed with amalgamed silk).

---

* See Appendix, V.

This is explained, or rather expressed, by the following hypothesis:—There are two kinds of electricity, of which that of the excited glass and that of the excited wax may be taken as representatives, and which may be called vitreous and resinous respectively. Electricities of like kind (or name) repel one another, electricities of unlike kind or name attract one another, and also each attracts neutral electricity; or, what comes nearly to the same thing, bodies similarly electrified repel, bodies dissimilarly electrified attract one another. The relation which the attraction of an electrified body to an oppositely electrified one bears to the attraction between an electrified body and a neutral one will appear in Art. 30, *et seq.*, under the head of *Induction.*

10. We may here, as always, assume, without any risk of error, that like actions with like materials will always produce like results: that one piece of sulphur rubbed with one piece of flannel will be in the same electric state as a second piece of sulphur rubbed with a second piece of flannel. Thus, returning to Art. 7, we shall find that two pieces of amber excited with flannel repel one another. Two sheets of brown paper excited by the clothes brush repel. If the silk ribbon, after excitement with vulcanized caoutchouc, be held in the middle, the two ends will repel one another. If the sheet of thin note paper, after excitement with the bottle caoutchouc, be cut into strips as it lies clinging upon the hot board, and be gathered together at one end and lifted from the board, the strips will start asunder. Collodion, excited by the fingers and hung by a thread, is repelled by similarly excited collodion.

Finally, if we compare the different substances above mentioned, when electrified, with one another, and arrange those which repel one another in two vertical columns, in such a manner that each substance repels all those in its own column (and is, therefore, similarly electrified with them), but attracts those in the other column, we get experimentally the following result:—

(Rubbed with)	1.	2.	(Rubbed with)
Amalgam on Silk,	*Glass*	*Sealing-wax,*	Flannel
Bottle Caouchouc,	*Paper*	*Sulphur,*	Flannel
Vulcanized Caouchouc,	*Silk*	*Collodion,*	Fingers
		Brown Paper,	Hog's Bristles
		Amber,	Flannel

11. The electricity in the glass, paper, and silk, excited as above, was at one time called vitreous, glass being taken as the representative substance. The electricity of the substances of the second column was called resinous, because amber and sealing-wax (which should consist mainly of shell-lac) are resinous bodies.

12. The terms vitreous and resinous are now scarcely used; for it was soon found that the kind of electricity developed on a body depends quite as much upon the nature of the body with which it is rubbed as upon its own nature. Thus, while glass rubbed with silk or amalgamed silk is vitreously electrified, when rubbed with flannel it becomes resinously electrified; and even some resins, when rubbed with cotton, become vitreously excited.

13. Positive and Negative.—Instead of the terms vitreous and resinous, it is now usual to use the terms positive and negative respectively, or their corresponding symbols, + and −. The reason for the use of these terms, conveying, as they do, a definite relation in kind, is derived from the following facts and considerations:—If two unelectrified bodies, A and B, are rubbed together, and, after separation, one of them, A, is found to be charged with one kind of electricity, the other, B, is invariably found to be charged with the other kind. Not only so, but, as far as one can measure, the quantities of the two kinds are equal. Thus, each will attract a third neutral body, C, with the same mechanical force when at the same distance from it. And if the two bodies, A and B, be left together after rubbing, or be brought together after separation, they will have together no joint mechanical effect upon C (see Art. 25). The two kinds of electricity neutralize one another's effects, and are in so far related to one another, like the operations of addition and subtraction of equal quantities. Further, if one body, A, be strongly charged with one kind, and another, B, be less strongly charged with the other kind, the two when brought together will have a joint effect upon a third, in kind that of the most powerful, A, in quantity that of their difference, A − B. Just as in most cases of terrestrial mechanics, we may consider the earth to be at rest; so the earth and bodies in good electric connection with the earth, or such as have recently been so, are considered electrically neutral. Not in the sense of having no electricity of either kind, but as having the two kinds in the same proportion as they exist in the earth itself, and, therefore, being no more attracted than repelled electrically by terrestrial objects. We may, in fact, conceive the two electricities to be related to one another in something the same manner as the two elements of common salt—chlorine and sodium—which, when united in certain proportion, produce a neutral salt, whose union is attended not by a destruction of either element, but by a balancing of their chemical activities. When two dissimilar electrically neutral substances are rubbed together, it is usual to suppose that the neutral electricity at their common surface is decomposed; and when the two substances are separated, an excess of one kind of electricity is found upon the one, and an exactly equivalent quantity of the other kind upon the other substance (see Art. 25.)

14. It need scarcely be remarked that the word "negative" is used in English in two distinct senses. In one sense it expresses the absence or lack of a thing, in the other a direction to subtract. The assertion of the existence of a negative quantity in the sense of a quantity less than nothing, either of matter or property, is a contradiction in terms, and is absurd. But the terms positive and negative, as applied to the two conditions of electrical state, are useful, in so far as they indicate the power which the two have of neutralizing one another's activity.

15. If any two of the substances in the following list are rubbed together, the one nearest to the top of the list is found to be positive to the one below; that is, the upper one acquires +, the lower are – electricity. Such a list, however, has only approximate exactness. Thus, the following metals become + electric when rubbed with flannel: bismuth, zinc, lead, copper, brass, silver, and silver amalgam; the following become – with flannel: arsenic, antimony, tin, iron, nickel, gold, platinum, and palladuim. Indeed, in the case of the oxidizable metals, the electricity may be due to the friction between the metal and its oxide rubbed off, and may be of a different kind from that between the clean metal and the rubber.

+
Fur,
Flannel,
Ivory,
Quartz,
Wood,
Shell-lac,
Resin,
Metals,
Glass,

+
Cotton,
Silk,
The Hand,
Sulphur,
Vulcanized Caoutchouc,
Ebonite,
Caoutchouc,
Gutta Percha,
Gun-cotton (Collodion).

16. Proof Plane.—For the detection of small quantities of electricity, the determination of their kind, and the examination of the isolating or conducting powers of bodies, the proof plane and electroscope are of great use. The proof plane is made by sticking metal leaf or foil upon both sides of a piece of paper or cardboard, cutting out a circular or elliptic disk with smooth edges, and fastening it by a little melted shell-lac into a slit cut in the end of an ebonite penholder, or upon a varnished glass rod or tube. The metal covering the disk being a good conductor, and the ebonite or glass a bad one, when the thin end is held in the hand and an electrified body touched with the disk, the latter immediately becomes charged with electricity which cannot escape along the ebonite; so that, on removing it from the body, we have at our disposal a sample of the electricity under examination. Such proof planes, when hung by silk or cotton in a wire stirrup (Art. 8), or supported upon a needle-point, may very conveniently be used as masses of movable electrified or neutral matter. An ebonite penholder thrust through a cork bung forms an excellent proof plane.

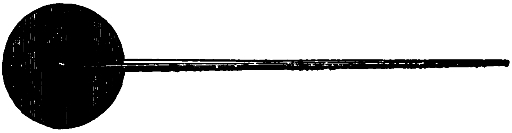

Fig. 5.

17. Electroscope (Pith Ball and Gold Leaf).—The pith-ball electroscope consists of two balls of elder pith of the size of a pea, hung side by side on cotton threads fastened to a knob or plate, with which the body supposed to be electrified is brought into contact. The wire connecting the knob with the cotton thread is coated with shell-lac, and passes through a plug of wood in the neck of a bell-jar resting on a wooden stand (fig. 6). An electrified body brought into contact with the knob gives up a part of its electricity to the knob, and thence through the cotton threads to the pith balls, which, being therefore similarly electrified with one another, repel and diverge. The gold-leaf electroscope is based upon exactly the same principle. A circular brass plate A (fig. 7), having rounded edges, carries a stout brass wire B, cemented by shell-lac into the glass tube C, which passes through the wooden cap D; fitted by a groove upon the top of the bell-jar F. The lower end of the wire carries a horizontal brass cross-piece E, about an inch in length, flattened in a vertical plane, and very thin. Each side of E is smeared with a little strong gum, and laid upon the edge of a rectangular strip of gold leaf,* about 1 in. by 5 in. The leaves hang thus face touching face. On the inside of the bell-jar, opposite to one another, and each facing one of the gold leaves, are sometimes pasted two strips of tin-foil of such a height that they are touched by the leaves on the extreme

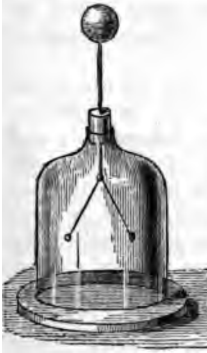
Fig. 6.

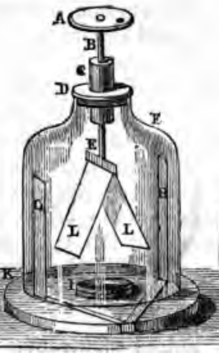

Fig. 7.

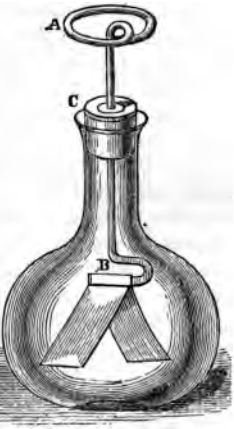

Fig. 8.

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* See Appendix, VI.

divergence of the latter. These strips reach to the stand K, if it be of metal; or if it be of wood, they are horizontally prolonged and carried over the edge to the earth. A shallow cup, I, contains quick-lime, chloride of calcium, or strong sulphuric acid, to keep dry the inside of the jar. A very simple and efficient form of electroscope is made by bending a stout copper wire, as in fig. 8, so as to form a horizontal ring A. The lower end B, bent into a shallow hook, is hammered flat to receive the gold leaves. The wire passes through a large hole ¾ in. in diameter, in a disk of wood or metal C, in which it is fixed, and from which it is electrically isolated by abundance of shell-lac. The disk C is fastened by a little soft wax* upon the top of a flask of about 4 litres capacity. A little sulphuric acid may be placed in the flask; but, even without this, such an electroscope scarcely loses any of its charge in five minutes, and retains a considerable amount after the lapse of several hours.

18. Conductors and Non-Conductors.—By the use of the electroscope, the relative conducting powers, or "conductivities," of various substances have been determined; and the chief results may be easily verified. If, for instance, we fasten a dry silk thread, four or five yards long, to the top of the electroscope, and loop the other end round a glass tube, we find that, however the tube may be excited by rubbing it with amalgamed silk, the leaves remain at rest. Accordingly, silk is a non-conductor, and may be used as an isolating support. So, if we take a long thread of shell-lac, dry glass, ebonite, vulcanized caoutchouc, or of sulphur, and resting one end on the electroscope, touch the other with any excited substance, the leaves remain at rest. These substances are almost perfect non-conductors or isolators. If, on the contrary, any metallic wire be employed to connect the electroscope with the glass, the leaves diverge the instant the latter is excited, although the wire be exceedingly thin, and twenty or thirty yards in length. Again, if the silk thread employed in the first experiment be wetted, it will no longer isolate, but conduct with great ease, proving that water is a far better conductor than silk.

The following list shows, approximately, the relative conducting powers of various substances. The metals and some forms of carbon are so pre-eminent as conductors, that they may be considered as forming a class by themselves. The metals are the best, and paraffin the worst of conductors:—

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* See Appendix, VII.

Metals.
Gas Coke.
Graphite.
Solutions of Hydrogen Salts.
Solutions of Metallic Salts.
Metallic Sulphides.
Water.
Metallic Salts (solid).
Linen.
Cotton.
Hemp.
Paper.
Alcohol.
Ether.
Dry Wood.
Dry Ice.
Metallic Oxides.
Ice at $-25°$C.
Fats and Oils.
Caoutchouc.
Gutta-percha.
Dry Air, Gases, and Vapours.
Wool.
Ebonite.
Diamond.
Silk.
Glass.
Wax.
Sulphur.
Resins.
Amber.
Shell-lac.
Paraffin.

It may be observed that the entire subject of conductivity for frictional or static elasticity, especially with regard to bodies which are not organised, and have a definite chemical constitution, such as the liquid and solid hydrocarbons, alcohols, acids, fats, ketones, etc., requires further examination. Bodies, whether natural or artificial, which have no constant composition, such as the resins, gutta-percha, or ebonite, necessarily vary in their insulating power; and the same is true with regard to organised bodies, such as cotton, silk, wool, and wood, and even with those which have chemico-mechanical (crystalline) structure, such as most solid elements, salts, and other definite chemical combinations.

19. The moisture in the human body and on the skin makes it, in most circumstances, a good conductor. Hence all electrified substances when freely handled are discharged, and good conductors instantly lose their electricity by mere momentary contact in one place with the fingers. To this is attributable the long oversight of many cases of electric excitement.

20. The most usual form of isolators are stems of varnished glass, ebonite, sheets of vulcanized caoutchouc, sheets of ebonite, or of varnished glass, stems and sticks of sealing-wax or shell-lac, sheets of paper soaked in paraffin, threads of cocoon (undyed) silk, etc. Electric conductors, or connectors, are usually made of metallic rods, chains, or wires (thin copper wire). Bodies which are to serve as collectors or reservoirs of electricity (often called conductors), may be made of sheet brass, round-ended cylinders, or globes, or of wooden cylinders, or spheres covered with tin-foil,* supported on thick glass or ebonite stems.

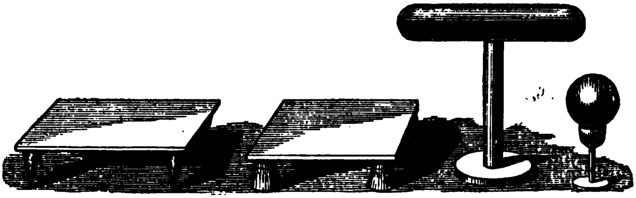

Fig. 9.

21. Electrification by Contact.—When an electrified body is brought into contact with an unelectrified or neutral one, there is always, at the point of contact, a passage of electricity, of such a kind as to bring the two points of contact into the same electrical state. If one only of the two bodies be a good conductor, the establishment of similar electricities will be very limited in extent and small in quantity; but if both be good conductors, the establishment of identical electrical state in the two will be perfect and immediate. According to the generally adopted view when, say, a neutral proof plane touches a + ly electrified one, a certain quantity of + electricity leaves the + ly electrified plane, and, at the same time, an equal quantity of − electricity leaves the neutral plane to enter the electrified one. These two quantities neutralise one another, and the result is,

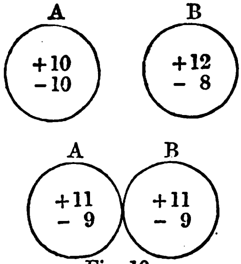

Fig. 10.

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* See Appendix, VIII.

that both bodies are ultimately left in the same state of + excitement, less intense than that of the originally excited plane. Thus, let the matter A (fig. 10) be neutral, having an amount of electricity, which we may represent by, say, twenty arbitrary units, *viz.*, 10 + and 10 −. Let there be the same total quantity of electricity in B, but let this consist of 8 − and 12 +, thus having a balance of + 4. On contact, we may suppose B to lose 1 + and gain 1 −, and A to lose 1 − and gain 1 +, the electric state of both being thus brought to + 2.

It is clear that, conceiving as before a neutral body A (fig. 11) to be represented as having − 10 and + 10 electricities, we might suppose a + ly electrified one B to be represented by − 10 and + 12, and we might suppose the equalization of the electric state of the two bodies to be due to the passage of + 1 from B to A. It must be remembered that there is no direct evidence to show that the latter supposition is not the true one. We shall return to the consideration of this point in Chap. II., on *Induction;* for the present let us consider that when a neutral proof plane is passed along an excited glass tube, it receives a certain amount of +, and gives up an equal amount of − electricity, by both of which it acquires an excess of +, and by both of which the charge on the glass is diminished. On bringing the so charged proof plane in contact with the top of the electroscope, precisely the same kind of interchange of electricities takes place, and the leaves diverge with + electricity.

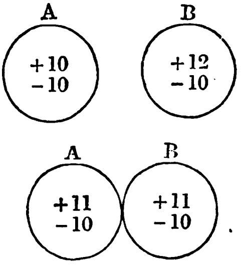
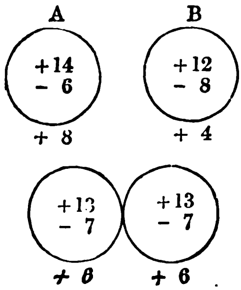


Fig. 11.

22. Testing Electricity by Contact.—By the electroscope and proof plane, we have now the means of testing with what kind of electricity we are dealing in any case. Thus, suppose we wish to know whether the electricity of sulphur, which has been rubbed with flannel, is + or −. Excite a glass tube with amalgamed silk; move along the surface of the tube the proof plane so as to ensure many points of contact with the tube: otherwise, the glass being a non-conductor, the plane will be imperfectly charged. Touch the electroscope with the proof plane, and the leaves will diverge with + electricity. If, now, the proof plane be discharged by touching it with the fingers, and brought into contact as above with the sulphur rubbed with flannel, and then with the electroscope, three things may happen: (1) the leaves will partially collapse; (2) they will completely and exactly collapse; (3) they will collapse and again separate. If (2) takes place, it follows that after contact both the proof plane and electroscope are neutral; but since the electroscope had an excess of +, it follows that the proof plane, and therefore the sulphur, must have been negative. If the (3) event occurs, the collapse of the leaves proves that there was sufficient - on the plane to neutralise the + in the electroscope, and the subsequent separation of the leaves proves that there was more than sufficient to do so, the leaves, in fact, separating by electricity of the opposite kind; we therefore again conclude that the sulphur was - . If (1) the leaves only partially collapse, we prove nothing conclusive; for though a quantity of - electricity in the plane, insufficient to neutralise the whole of the + in the electroscope, would produce this effect, the same result would follow on bringing an isolated neutral body in contact with the electroscope; for then, as in Art. 21, such an interchange of + from the electroscope, and - from the neutral plane, would take place as would leave them both +, though not so strongly so as the electroscope alone was originally.

23. It is clear, therefore, that the partial collapse of the + charged leaves, when the proof plane touches the electroscope, does not prove that the plane is −. It may even be +, and yet produce this effect, provided it be more feebly + than the electroscope. Thus we may suppose the electroscope to be positive to the amount represented by A, namely, + 14, − 6. If then the plane be + to the amount represented by B, namely, + 12, − 8, their contact will produce a common condition



+ 13, − 7, and the leaves will therefore not diverge so far.

24. Charge now the proof plane − ly, as, for instance, by bringing it into frequent contact with excited shell-lac; touch the electroscope with the plane, whereupon the leaves will diverge with − electricity. Excite the sulphur with flannel, touch the sulphur with the proof plane, and with this touch the electroscope. If, now, the leaves separate further without previously collapsing, we have absolute proof that the plane, and therefore the sulphur, are − . For if they had been neutral, the leaves would have given − and received +, and partially collapsed; if they had been +, a still greater interchange of electricities would have produced a still further collapse, perhaps complete, perhaps followed by + divergence. It is clear that, by similar reasoning, a body must be + electrified if it causes continued or increased divergence in leaves already + diverged.

Practically, when we are testing by touch for, say, + electricity, it is convenient to give a small + charge to the leaves, so that the proof plane which is being tested may have a stronger charge than the leaves. Or if the electricity to be tested is feeble, the electroscope is first feebly charged with it, and then an abundantly charged proof plane containing the same kind as that suspected is brought in contact with it.

25. Electric Excitement is Due to Electric Decomposition.—We have hitherto only considered the electric state of one of the two bodies rubbed together: as *glass* when rubbed with amalgamed silk, *sealing-wax* when rubbed with flannel, etc. If now we examine the electric state of the amalgamed silk, we find it to be −, or opposite to that of the glass. Again, we find the flannel to be +, or opposite to that of the wax. This may be shown in several ways. Let the amalgamed silk be thoroughly isolated from the hand by being held in a sheet of vulcanized caoutchouc; after rubbing the glass, electricity may be taken from the rubber by a proof plane, and is found to be − . The "electric syringe" (fig. 12) is an instrument used to illustrate the same fact. A varnished glass knob A is fastened to a brass piston-rod B, which works through a brass cap C, and carries a piston D covered with amalgamed silk, which rubs the inside of the glass tube E. Fastened to the other side of the piston is a varnished glass rod F, which carries a spiked disk G, to which is fastened a chain H, the other end of which is fastened to the brass cap I at the further end of the tube. On moving the piston to and fro, + electricity is developed on the inside of the glass. This travels through the spikes of G (see Art. 58) down the chain to I. The - electricity of the rubber is conveyed along the piston-rod to C. Accordingly, we find that I becomes + and C -. A simpler method may be employed. Let a stick of sealing-wax be rubbed with a piece of flannel, and let them be placed side by side on the top of the electroscope: the leaves are not stirred; but if either one be removed the leaves diverge: the wax, when left alone, causing -, the flannel + divergence. A similar experiment with the glass tube and amalgamed silk confirms the above conclusion. The two experiments together may be taken as tending to prove not only that the two bodies rubbed together are oppositely electrified, but also that the quantities of the two kinds of electricity are in all cases sensibly equal or able to neutralise one another completely.

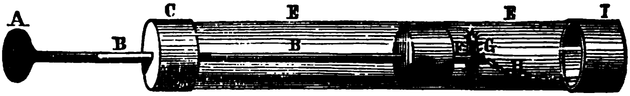


Fig. 12.

26. In order to procure a considerable amount of frictional electricity, it is clearly of advantage that one, at least, of the bodies rubbed together should be a non-conductor. For if both were good conductors, the electricity excited by their friction would be free to travel about their surfaces, and to pass from one to the other, so that neutralization would speedily ensue. So that, though in such cases large quantities of electricity may be developed, they are not apparent. Hence it is that we have shell-lac, sealing-wax, glass, sulphur, etc., which are non-conductors, so useful as "electrogens," that is, for forming one element in procuring frictional electricity.

27. If, however, a conductor be isolated, it may be used as an element of frictional excitement. Thus, a piece of leaden tubing, held in a sheet of vulcanized caoutchouc, and struck with flannel, is found to diverge the leaves with + electricity. The sheets of paper, as they issue hot-pressed from the metal rollers of the manufacturer, are strongly electrified.

28. Human hair, when clean and dry, or the fur of an animal, becomes + ly electrified when rubbed with the hand, or an ebonite comb, and they retain their electricity for some time (as does the comb) on account of being imperfect conductors. Mercury poured backwards and forwards from one varnished tumbler to another becomes + electrified. The electroscope itself becomes directly excited when its top is struck with silk or flannel.

29. The following substances amongst non-conductors become + ly electrified when rubbed with flannel: diamond, sulphate of potassium, nitrate of potassium, chloride of sodium.

The following amongst conductors become + electrified when rubbed with flannel: bismuth, zinc, lead, copper, brass, silver, mercury. (Comp. Art. 15.)

The following among conductors become – electrified when rubbed with flannel: rhodium, arsenic, antimony, tin, iron, gold, nickel, platinum, and palladium.

The following non-conductors become – ly electrified: sulphur, talc, etc.

Finely divided copper becomes electrical on compression. Dry oxalate of calcium, on being stirred with a glass or platinum spatula, becomes + ly electrified. When water freezes in contact with a metal, the metal becomes +.

The structure of the surface alters the nature of the electricity developed upon it. Thus smooth glass and rough (etched, ground) glass become differently electrified when rubbed with silk.

It has been supposed that the development of frictional electricity was due to chemical change; and that when frictional electricity, by attrition of bodies in the air, oxidation occurs on one to a greater degree than on the other, and it was supposed that the substance most facile of oxidation became invariably negative. Some experiments, however, seem to show that the same electrical relation is preserved when the friction between two bodies occurs in carbonic acid or hydrogen, as when it occurs in air.

Nevertheless, oxidation, or at all events the molecular motion which accompanies it, gives rise to electrical phenomena. Thus an isolated brazier containing burning charcoal is always negative.

CHAPTER II.

INDUCTION.

30. Induction.—When an excited glass tube is gradually brought near to the top of an electroscope, the leaves of the latter are seen to diverge, and to increase in divergence as the distance is lessened. On removing the tube, the leaves gradually collapse as the distance increases, until—it may be at two or three feet—the divergence becomes insensible. Exactly similar phenomena ensue if flannel-excited sulphur be used instead of the glass. The restoration of the leaves to their original neutral condition proves that no permanent loss of one kind of electricity, or gain of the other, has taken place in the electroscope, as is the case when it is charged or discharged by actual contact with the proof plane, or discharged by contact with the earth. The name induction is given to the influence thus exerted upon a neutral body by an excited one at a distance. The induction in the above instance takes place through air.

31. In order to determine, experimentally, whether the electricity thus temporarily induced in the electroscope is of the same kind or not as that of the glass, the following experiment may be tried. Connect the electroscope E (fig. 13) by means of a wire W, with one end of an isolated conductor C. The conductor, wire, and metal of the electroscope thus form, electrically speaking, one metallic mass. Bring now the + ly excited glass tube near to the further end of the conductor. The gold leaves will diverge by induction. While they are so diverged, remove the wire from the electroscope by means of some non-conducting substance, such as finger stalls of vulcanized caoutchouc, an ebonite penholder, or ebonite tongs (Art 72). The leaves remain now separated when the glass tube is withdrawn, and on testing them with a proof plane holding + electricity, they are found to be also + electrified.

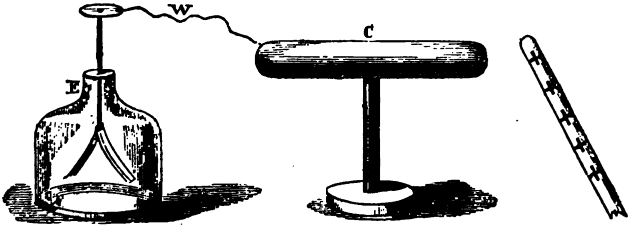


Fig. 13.

A similar experiment proves that when flannel-rubbed sulphur, or sealing-wax, is brought near to the electroscope, its leaves diverge with – electricity. In all cases the divergence of the leaves being due to the induced activity in them of electricity of the same kind as that of the excited neighbouring body. If we conceive the original neutral state of the leaves to be due to the balancing of equipotents of + and – electricities, we must look upon the glass tube as exerting its influence through the air, and neutralizing a portion of the – electricity of the electroscope, such neutralization being, of course, reciprocal. A portion of the + of the electroscope is thereby disengaged from its negative; + becomes free and causes the leaves to diverge with + electricity. Thus though the – electricity does not quit the electroscope, it is counteracted or paralysed, leaving the + free and active. That this view accords with facts is seen from the following experiments.

Bring the excited glass tube near the electroscope until the leaves diverge. Keeping the tube in its position, touch the electroscope with the other hand: the leaves immediately and completely collapse; remove the hand, and then remove the excited tube: the leaves will now separate, and on testing with flannel-rubbed sealing-wax they are shown to be – ly excited. This series of experiments is illustrated in fig. 14. The neutral electroscope is shown in 1. In 2, the leaves diverge with +, because the – is counteracted by the + of the tube; this counteraction is represented by the dotted line connection. In 3 the leaves are collapsing owing to the escape of + through the hand to the earth, and the advent of –. In 4 there is excess of – in the electroscope, but that is wholly paralysed by the – of the tube. In 5 the tube is withdrawn, and the leaves diverge with free –.

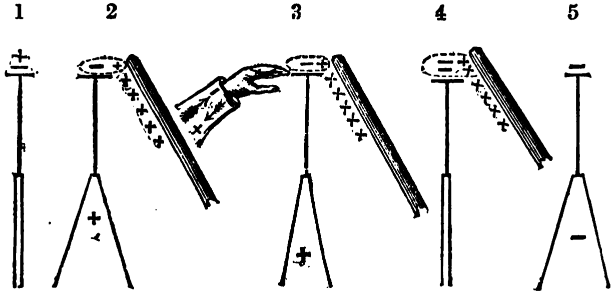


Fig. 14.

In a precisely similar manner the electroscope can be charged with + electricity, by bringing flannel-rubbed wax near it, touching it for an instant with the finger, and removing the wax.

32. Localization of Induced Electricity.—In Arts. 30 and 31, we have seen that a ± electrically excited body so neutralizes ∓ electricity in neighbouring ones as to set the ± electricities in those bodies at liberty, and so produce a provisional state similar to the permanent one which would have been produced if actual contact had taken place. We have now to consider the actual displacement in space which the two kinds of electricity undergo in the neutral body under induction.

Recurring to experiment of Art. 31, let the wire W be so carefully removed, by the isolating appliance, that it does not touch the earth when in contact with either the electroscope or conductor. Not only is it found that the electroscope is +, but also that the conductor is –. The – electricity in the neutral mass has, in fact, been attracted by the + electrified glass, and the + has been repelled therefrom.

The same principle is well shown by the following experiment. Let A and B (fig. 15) be two wooden spheres covered with tin-foil, and supported on isolating legs. Bring them into contact as 1. Bring near to B an excited + glass cylinder C, as 2. Remove A from B, and then the cylinder C from B. It is thus found that A is + ly, and B – ly charged. On bringing A and B together, half the excess of + in A goes to B, and half the excess of – in B goes to A. Both become again neutral, and this neutralization may be attended by a luminous discharge or spark.

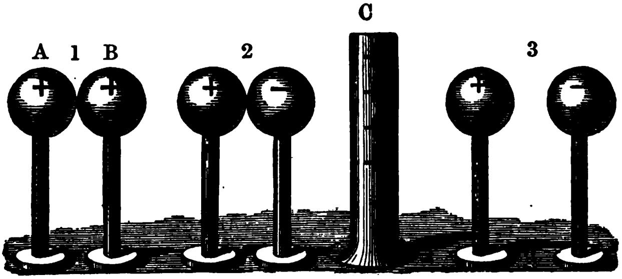


Fig. 15.

33. Again, if we take a single continuous conductor, isolated as before, and bring near one end of it the + excited cylinder C (fig. 16), we find that a proof plane P becomes

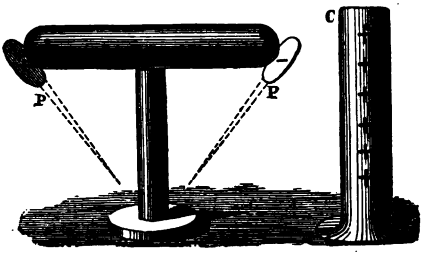


Fig. 16.

+ or – charged, according as we touch with it the end of the cylinder furthest from, or nearest to, C. When in contact with the cylindrical conductor, the proof plane forms, in fact, a part of it, so that removing the plane is equivalent to breaking the conductor, or separating its parts, as in fig. 15.

34. Further, instead of taking, as in Arts. 32 and 33, an isolated sample of earth, or neutral electricity, in the conductor for analysis, we may employ the earth itself to furnish us with neutral electricity for decomposition. Thus, let an excited glass rod be held within two or three inches of the earth, or of any conducting object or person standing on the earth, a proof plane which touches that object or person is found to be – ly charged. In this case, as in Art. 33, the proof plane, when touching the body whose electricity is undergoing inductive analysis, must be looked on as forming for the time a part of such body, and the removal of the plane as the breaking off of a part which shares in the general electrical analysis of the collective mass.

35. If, while an isolated conductor is suffering inductive analysis of its electricity by a, say, – ly electrified neighbour, the end nearest to the inducer is connected for an instant with the earth, and the inducer then withdrawn (fig. 17), the conductor is found charged with – electricity; whereas, if the other end be momentarily touched, an excess of + electricity is afterwards found.

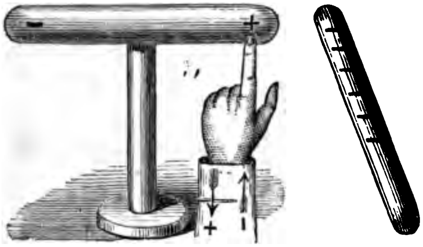


Fig. 17.

36. Again, if the two ends of an isolated conductor (fig. 18) are furnished with conducting uprights, from which pith balls, *a* and *b*, are hung by cotton threads, on bringing an electrified glass cylinder C near to one end, each ball will be repelled from its support, as in the figure. It is easily proved that they are repelled by reason of opposite electricities. For if a flannel-excited stick of sealing-wax be held near to *a*, it will be attracted, while *b* will be repelled; the reverse takes place if an amalgamed silk-excited glass rod be used.

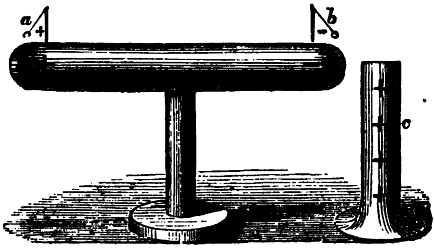


Fig. 18.

37. If a thoroughly dried card be rubbed with caoutchouc, and brought near one end of an isolated conductor, the other end of which is fitted with a stout wire terminating about ⅛ inch above a gas burner connected with the earth, the burner may be lit. For the sudden approach of the card, which is +, repels the + of the conductor, and attracts −. The interval between the wire and the burner becomes the field where + goes to earth, and − leaves the earth. That interchange is a spark which may light the gas. If, then, the gas be

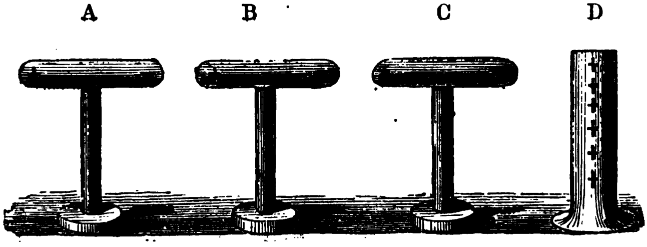


Fig. 19.

extinguished and the card suddenly removed, the gas may be again lit; for now the released − rushes to earth, and the no longer repelled earth's + resumes its share of the conductor.

38. The action of induction is propagated from mass to mass of conductors; the diminution appears to be due in an indefinitely greater extent to the magnitude of the air intervals, than to the length of the conducting substances. A succession of isolated condutors A, B, C (fig. 19) are placed end to end, and an excited glass cylinder D (+) is brought near to C. Each cylinder is found to be polarised, and from each end of each a proof plane may be charged with the kind of electricity denoted in the figure.

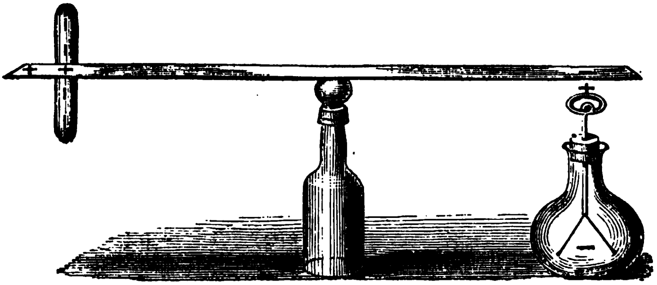


Fig. 20.

A variety of experiments may be devised to illustrate these facts. An instructive one is to balance one end of a lath over an electroscope, and make the lath revolve by attracting it with excited wax (fig. 20); every time the lath passes over the electroscope, the leaves of the latter diverge with − electricity.

39. Explanation of Electrical Attraction.—Amongst the earliest of our experiments were the attractions between neutral and electrified bodies (Art. 7). These can now be referred to inductive decomposition. Imagine that we have a + ly electrified body A (fig. 21), and that we bring near it an isolated neutral body B.

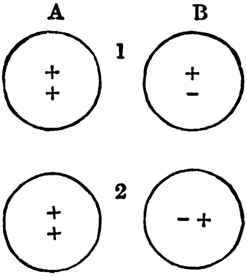


Fig. 21.

The + electricity of A attracts the − of B, and repels the + of B, so that if the two are restrained from moving, their condition is as in 2. The result of the local analysis of the electricity of B is that its – is drawn towards A, the + repelled. The attraction, therefore, between the – of B and the + A is greater than the repulsion between the + of B and the + A, because the former is exerted at a less distance than the latter. Attraction therefore prevails, and A and B are drawn together. The same inductive decomposition takes place when it is the earth's electricity which is decomposed, and hence an electrified body is attracted by the earth, or any body in electric contact with it.

The experiments of simple attraction, described in Art. 7, can now be better understood. The paper, for instance, rubbed with caoutchouc clinging to the wall is, by dint of its own + electricity, holding the earth's – electricity in its own neighbourhood, and repelling the earth's + electricity. The paper being an imperfect conductor, and not touching the wall over its own whole surface, the two electricities do not immediately combine to neutralise one another. A good conductor, when electrified and attracted to a conducting part of the earth, is immediately discharged on touching it, by the union of the body's electricity with that of the opposite kind of the earth.

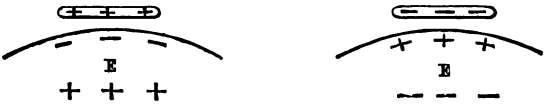


Fig. 22.

It is impracticable to alter the electric condition of the earth by pouring into it, from any artificial source, electricity of one kind, because, as far as is known, the development of one kind of electricity is accompanied by the development of an equipotent of the other. Both ultimately reach the earth, which serves as an inexhaustible storehouse, or "common reservoir," for electricities of both kinds. The slight separation and temporary isolation of any quantity of electricity of one kind which we can effect, is quite inadequate to influence appreciably the general neutrality of the earth-mass.

40. Attraction followed by Repulsion. — Whenever attraction between an electrified and a neutral body, both of which are isolated and good conductors, causes them to touch one another, repulsion immediately ensues. For the mixture of neutral electricity with either + or − must result in a + or − mixture, which condition, being shared by both bodies, must result in their repulsion. Thus the neutral body A (fig. 23), and the + body B attract till they touch and then repel, both being +. Similarly, C and D before contact attract, but after contact, both being −, they repel. When the two isolated conductors which attract are neither of them neutral, but in opposite states, there is only one case where repulsion does not ensue after contact, and that is the case where the two kinds are exactly equipotent, as between A and B (fig. 24).

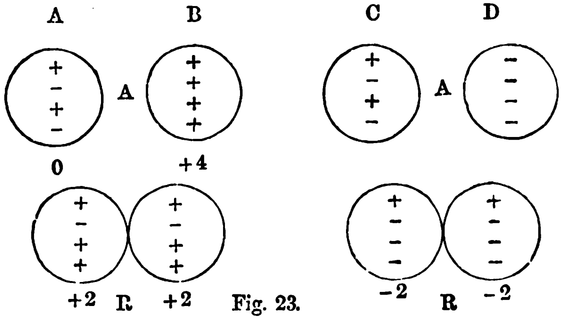


Fig. 23.

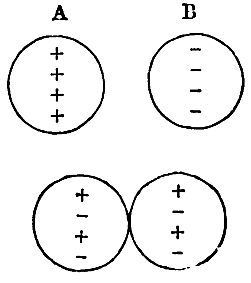


Fig. 24.

In all other cases, more or less, repulsion must ensue. For unless there be perfect equality of amount, and opposition of kind, the residue or difference has to be shared.

41. An instructive experiment, which illustrates several of the principles which we have hitherto been describing, is the following: Let the two isolated tin-foil coated spheres A and B (fig. 25) be brought into contact, and subjected to the local analysis of their electricities by a + excited glass cylinder (Art. 32, fig. 15). When separated, and the cylinder removed, we have A + and B – . Set up between the two a balanced proof plane (Art. 16); it will oscillate backwards and forwards between A and B for a long time. The plane, to begin with, is inevitably a little nearer to one sphere than to the other. The two spheres assist one another in the inductive analysis of the neutral electricity of the plane. The plane moves to the nearest, say to the – sphere, touches it, and partly neuralises it, giving it + and receiving –. It is now repelled by the –, and more strongly attracted by the + sphere. It swings to touch the + sphere, to which it gives up its –, and receives an excess of +, thus weakening the – charge in the + sphere. It is now repelled by the + and attracted by the –, and so on.

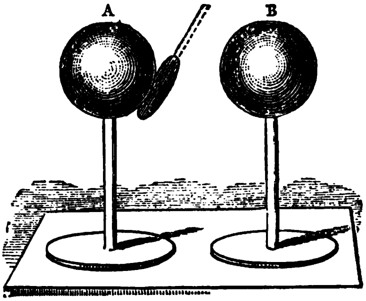


Fig. 25.

42. Testing Nature of Electricity by Induction.—In Arts. 22, 23, 24 were described the means for testing the nature of electricity by touch, and the precautions necessary to be taken. In many cases, especially when non-conductors are concerned, it is difficult to get a clear result by means of the plane, partly by reason of the difficulty of charging it fully, and partly because the friction of the plane upon the body under examination is itself a source of electricity. *By employing* induction, this difficulty is overcome. The *electroscope is charged* by touch with the proof plane, or by the method of induction and touch (Art. 31). The body to be tested is then simply brought gradually towards the electroscope. If increased divergence ensue, we know that we are dealing with electricities of the same kind. If the leaves do not further diverge, they are discharged and recharged with the opposite kind of electricity, and the body to be tested is again brought gradually near.

Numerous other cases of inductive action may be well deferred until we are acquainted with the construction and use of "electrical machines," and the "quadrant electrometer," or quadrant electroscope.

43. The Electrophoros and Kindred Machines.—The inductive decomposition which a quantity of electricity of either kind effects in the neutral electricity of the earth (Art. 39), may be employed for obtaining an indefinite and, indeed, unlimited amount of electricity from the earth by means of one and the same quantity of free electricity. The action of the electrophoros is based upon this principle. A mixture is made of resin, shell-lac, and Venice turpentine.* This is poured into a wooden cylindrical dish, 2 or 3 inches deep, and 12 or 13 inches in diameter, lined with tin-foil. Any bubbles which arise, as the substance hardens, are burst by sweeping the surface with an air-gas flame. When quite cold, the cake C (fig 26) is removed with the foil adhering to it. It is placed upon a smooth wooden board B, and the foil F around its edges is pressed down on the board, and connected with a strip of foil *f* touching an upright pin P in the board. A circular brass plate L, somewhat less in diameter than the cake, furnished with a brass knob K at the edge: an isolating varnished glass handle O in the middle, completes the apparatus. The pin P is put in connection with the earth. In figs. *a*, *b*, *c*, *d*, the thickness of the cake, and also that of the brass plate, are much exaggerated for the sake of clearness. The cake is beaten with cat's skin or flannel; its upper surface becomes –; and the amount which it receives is augmented by the accumulation of + electricity on the tin-foil F derived from the earth. The corresponding – of the earth's electricity is the exact equivalent of the + developed on the cat's skin. We get thus the condition represented in *a*. The neutral brass plate is now placed on the excited cake. The neutral electricity of the plate is inductively decomposed, its – being repelled and becoming free (*b*), the + being drawn towards the cake's surface and there "fixed." Scarcely any actual interchange between the + of the brass and the – of the cake takes place, because the two surfaces only touch one another in a few points, and the resinous surface, being an exceedingly bad conductor, does not permit the recharging of the discharged points. When the brass plate is placed upon the cake, some of the + of the lower tin-foil passes into the earth, being, as it were, released from duty, while some – enters the foil from the earth by the same path. On touching the knob of the brass plate with the finger (*c*), – electricity escapes through the body to the ground, and additional + enters the plate. Indeed sufficient + is thus accumulated in the plate to inductively neutralise nearly the whole of the – of the cake, so that *scarcely any + remains* condensed on the lower foil. The

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* See Appendix, IX.

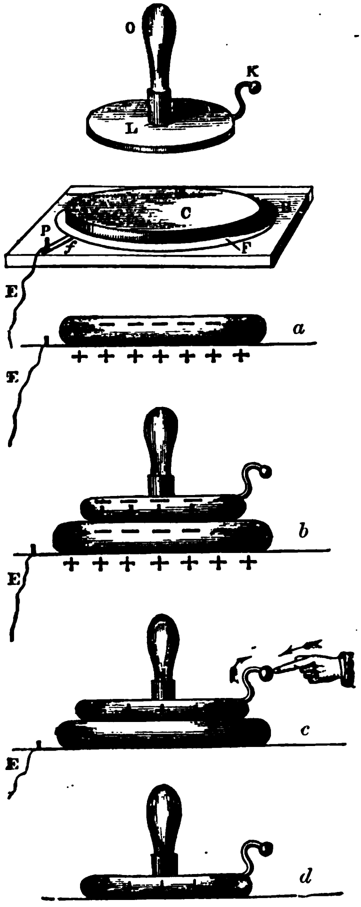

Fig. 26.

The brass plate being now removed by the isolating handle *d*, a + spark may be drawn from it by an earth-connected body, whereupon, of course, – enters from the body.

As the plate with its + charge is withdrawn from the – ly charged cake, + electricity again collects upon the tin-foil, and the condition of *a* is resumed. In this way an indefinite number of sparks may be obtained by once exciting the cake – ly, putting on the brass plate, touching it, and withdrawing it.

44. The resinous cake of the electrophoros may be replaced by any non-conducting and excitable substance, such as varnished glass, vulcanized caoutchouc, paraffin, or that compound of caoutchouc, gutta-percha and sulphur, which is called ebonite. All these substances become – electric when rubbed or struck with fur or flannel. The last becomes + ly electric when rubbed with amalgamed silk. When no very powerful spark is required, the above substances being permanently excited, a smooth-edged disc of zinc or tinned iron, held by a stick of sealing-wax, may be used to replace the brass disc. The electrophoros forms a convenient source of electricity when a single electric discharge is required at uncertain intervals of time; for the excited resin will retain its ready charge for days together; and the resinous surface is more dried, and is of itself less hygroscopic than the substances used in the "electrical machines" to be hereafter described.

45. For small charges, such as that required for charging the jar of the electrometer, to be described in Art. 136, a small hand electrophoros is useful. This consists of a circular disc of ebonite *a*, fig. 27, cemented on to a brass disc *b*. A little metal pin *p* passes from the brass through the ebonite to the exposed surface of the latter. A brass disc *c* is held by the insulating handle *h*. This compound disc *b a* is held by the brass as in the figure, and the ebonite is rubbed on any woollen surface, whereby it becomes – ly excited. On pressing the disc *c* upon the ebonite, the – electricity, set free in *c*, escapes through *p* to *b* through the hand to the earth, while + moving in the opposite direction collects in *c*, which accordingly becomes charged with free + when it is removed from *a*.

Comparing this effect with what has been said (Arts. 32 and 33) about the localization of the decomposed electricity, we might perhaps expect + to be discharged from *c*, since it is that kind which doubtless accumulates on the side of *e*, which is nearest to *a* as the two approach. But when actual contact ensues, the – of *c* can find a region yet more remote from *a*, by travelling down *p* to the earth; while the earth supplies + through *p* to *c*, which thus becomes + throughout.

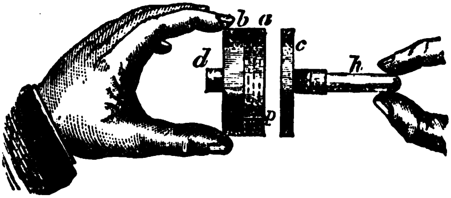

Fig. 27.

46. Successful attempts have been made to employ the inductive decomposing power of a given quantity of electricity, as a means of obtaining electricity of both kinds, without the continual labour of lifting or moving the charged or chargeable body. Instruments based on this principle are called continuous electrophoroi. But as their action includes the relation of points to electrical discharge, that is, the distribution of electricity on acutely angled surfaces, and its escape from, and collection by, conducting points, we must defer the description of such electrophoroi till after the next chapter.

CHAPTER III.

DISTRIBUTION.

47. Elementary Notions of Distribution.—Since the electricity on an insulated conductor repels itself, and, inductively decomposing the neutral electricity of surrounding bodies, attracts and is attracted by their electricity of the opposite kind, it is almost self-evident that the general distribution of electricity on a conducting body is mainly at its surface. It may also be admitted that the distribution of electricity on a spherical surface is uniform, when the sphere is uniformly surrounded by electro-inducible matter. If, for a moment, the electricity be compared with a ponderable fluid, we should, in the case of a spherical charged electric conductor, find the electric fluid to have a uniform depth or thickness throughout, and since the electricity repels itself, it must have throughout a uniform tension,* or tendency to separate from itself, comparable to the elastic tension of a compressed gas. Thus, if two pair of pith balls be hung by equal lengths of cotton from any two points of a spherical conductor (fig. 28), each pair will diverge when the conductor is charged, and the divergence will be to the same amount.

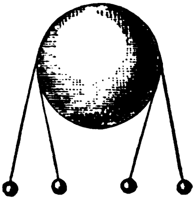

Fig. 28.

48. That electricity abides on the outer surfaces of bodies, may be experimentally proved in a variety of ways. Thus (fig. 29), a sheet of tin-foil F is fastened by one edge to a varnished glass rod R. The opposite edge is connected with

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* The term tension, as applied to electricity, will be more fully discussed in Chap. X., in considering electrical potential

the electroscope E. The rod is held in the hand, and successive charges from a proof plane are given to the foil, until the leaves of the electroscope begin to stir. The rod is then turned so as to roll up the foil, and as this takes place the leaves further diverge. The self-repelling electricity of the foil shuns the rolled-up portion thereof, where it would be amassed upon itself, and seeks the yet flat portion of the foil and the electroscope, where, for the same amount of surface, there is less contiguity of parts. There it accumulates as the foil is rolled up, increases in tension, and causes the leaves to diverge further.

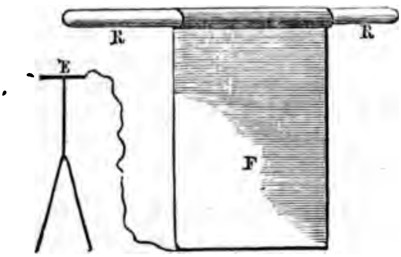

Fig. 29.

49. A truncated conical net of cotton N is fastened (fig. 30) below to a sheet of brass B; above to a hoop of wire H, which is attached to a varnished glass handle G. Whether the net or metal disc B receive a charge on the outside or inside, and whether the charge be + or −, it is found on the outside alone. And if the net be turned inside out by inverting it, the electricity immediately leaves the surface where it was and passes to the outside, as is proved by testing the outside and inside by a proof plane. A complete conical net may be supported on an isolating stand, with its mouth vertical, and be turned inside out by a silk thread passing through its apex, when a similar distribution of the electricity is observed.

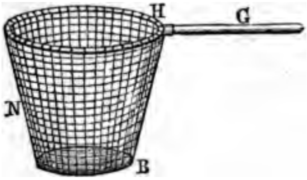

Fig. 30.

50. Electroscopes, which are used in lecture theatres and laboratories, where large quantities of electricity are developed, are frequently protected by cotton nets covering their plates; and such nets need not necessarily touch the table. Men and other animals may be placed in metal cages, which may be strongly electrified, without the animals suffering any inconvenience. (Compare also Art. 134, where the geometrical relation between distance and amount of inductive decomposition is considered.)

51. A foil-covered sphere A, fig 31, is hung by a silk tape T, and electrified. It is then clasped by two metal hemispherical cups C, held on isolating handles H, in such a way that the sphere is touched by each cup. On removing the cups, they are found to be charged on the outside, but there is no electricity on their insides, nor upon the internal sphere. We may conclude that, on clasping the sphere with the hollow hemispheres, the electricity immediately travels to the outside of the latter. And, indeed, on testing the outside of the hemispheres before removing them, it is found that the electrical tension on them is only less than that which was on the central sphere by an amount due to their greater surface.

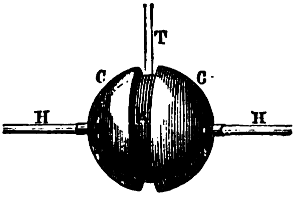

Fig. 31.

52. It appears, then, from experiment (Arts. 48 to 51) that, broadly speaking, free electricity at rest, or static electricity (1) dwells on the surface of conductors, and (2) that it shuns concavities. Both these propositions require some care in their application. Thus, a metal rod or wire, varnished with shell-lac, conducts as freely between any two exposed points of its surface as though it were naked. Its conducting power is not diminished when it is wetted with some non-conducting hydrocarbon, such as turpentine. We must admit, then, that the term electric fluid is so far inapplicable that, either remaining totally exterior to the conductor, the electricity demands no room above its surface, and so has not necessarily thickness, or that it can and does pass through the mass of the conductor, as we shall see to be the case with voltaic or dynamic electricity.

Again, in examining the inside of a vessel for electricity, if, as in fig. 32, one part of the proof plane be above the edge of the vessel when contact is made, the plane will become charged. For when thus in contact, the upper part of the plane forms a projecting portion of the general exterior convex surface, and is subject, like the outside of the vessel, to the inductive action of surrounding objects. Thus, although no free electricity can be detected on the inside of the vessel by a proof plane wholly within the vessel, this is due not to the absence of electricity, but to its self-repulsion and its attraction to the opposite kind of electricity, which is the result of its inductive action on surrounding objects, including air. There is, in fact, no electrical discontinuity between the inside and outside of the vessel.

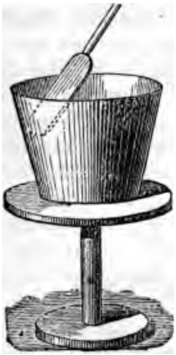

Fig. 32.

53. That the localization of free electricity on the outside of a hollow vessel is mainly due to induction is well shown by bringing (fig. 33) a metal earth-connected sphere *s* into a hollow metal isolated cup C, without touching it. On charging the cup while the sphere is in

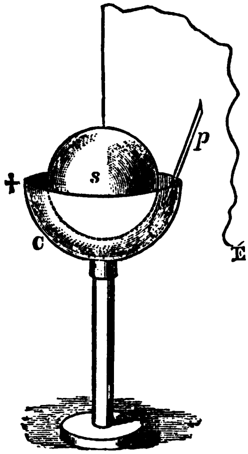

Fig. 33.

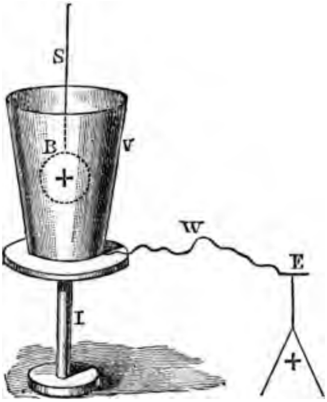

Fig. 34.

it, the electricity can be drawn by a proof plane *p* from the inside of the cup, but not from the outside. When the sphere is removed, the electricity passes to the outside. The change in position from the inside to the outside, and *vice versâ*, may be thus effected an indefinite number of times. The hand plunged into a charged and isolated tin pan will thus enable us to obtain a charge from the inside.

54. The effect of induction in determining the distribution of electricity on a conductor is again exhibited in fig. 34. A metallic vessel V stands upon an isolating support I, and is connected with an electroscope E. A foil-covered sphere B, hung from a silk thread S, and charged with + electricity, is lowered into V. At some distance above the upper rim of V the leaves of E begin to diverge with +. This divergence attains its maximum when the ball is a little below the rim of V (the precise distance depends upon the relative sizes of B and V, and on the shape of the latter). On lowering B no further divergence of the leaves occurs. Even when the bottom of V is touched, the charge in E is not increased. If, after contact with the sphere, B is withdrawn, it is found to have wholly lost its charge, in accordance with Arts. 49-52. When at or below the point at which the maximum divergence occurs, the sphere, of course, gives electricity to a proof plane in contact with it; for such a plane forms for the moment a part of the inner mass.

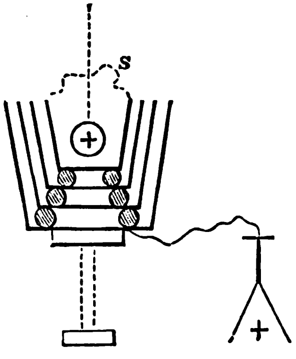

Fig. 35.

Further, several such vessels (fig. 35) being placed one inside the other, being isolated from one another by lumps of shell-lac, the whole isolated, and the outside vessel being connected with the electroscope, a charged isolated sphere sunk into the inner vessel causes the leaves to diverge. After touching the bottom of the inner vessel with the sphere, and removing it, whereby, as before, it becomes completely discharged, the innermost vessel may be lifted out by a silk thread S, whereupon the leaves collapse.

55. The **Tension Balance**, to be described in Art. 135, or that of Art. 136, may be used for measuring the tension of the electricity on the different parts of an irregular-shaped conductor; that is, for measuring the distribution of such electricity. When a point of a conductor is touched by a proof plane, the latter forms a portion of the conductor, and the quantity of electricity carried off by the plane on its removal is not independent of the attitude which the two have towards one another. And this is especially important when the proof plane is of a sensible size in comparison with the electrified body. By using delicate electrometers and small planes, we may, however, get approximate measurements; the latter condition also avoids the disadvantage of diminishing the charge by the process of testing.

56. The following example well exemplifies the relation between the tension of the electricity and the attitude of the surface of the conductor to surrounding bodies and to itself. Two equal metal spheres, A and B, are brought into contact at C, and charged with (say) + electricity (fig. 35*a*). From D, the centre of A, imagine a cone DF, drawn tangent to B; and from E, the centre of B, a cone EG, tangent to A. Lastly, let the spheres be enveloped in the tangent cylinder OP.* At C no electricity can be detected; at H and K it is faintly perceptible. At L and M there is a sudden increase, which gradually continues to O and P and which the surface (considered as a whole) of the two spheres becomes convex. The points Q and R, the extremities of the diameters through the point of contact, are the points where the tension is greatest.

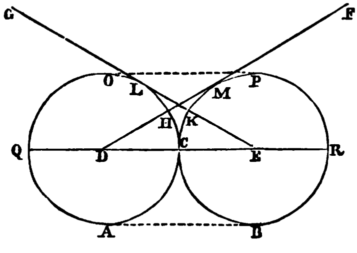

Fig. 35*a*.

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* In the figure the linear sections of these surfaces are shown.

57. Frictional electricity, being thus subjected to the inductive action of surrounding neutral bodies, as must always be the case near the earth's surface, collects on the surface of the electrified bodies. We should expect to find it, accordingly, in greatest quantity on those parts of a body where the surface is greatest in comparison to the mass. When a solid changes its size without changing its shape, the solid contents vary as the cube, the superficial as the square, of the linear dimensions. It follows that, where the curvature of a convex surface is greatest, that is, where the radius of curvature is least, there the tension of the electricity will be greatest. Accordingly, if we fasten pith balls to cotton threads, and hang pairs of such at different parts of an irregular conductor, their degrees of divergence are greatest where the radius of curvature is smallest. We may represent the tension of the electricity on the various parts of a conductor by the depth of some hypothetical atmosphere, or ocean surrounding the conductor, under the distinct understanding that no such voluminous atmosphere or ocean is known to exist. In fig. 35*b* the isolating supports are omitted, and the limit of the atmosphere, whose depth is supposed to represent the tension of the electricity, is represented by a dotted line.

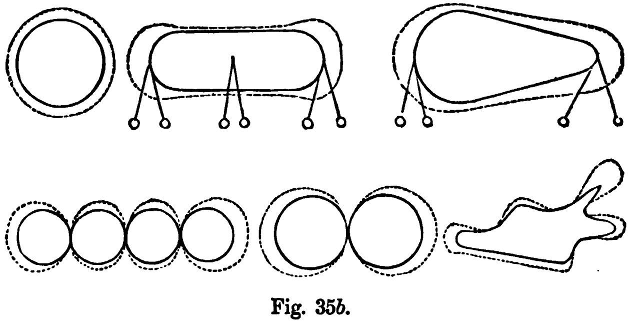

Fig. 35*b*.

58. If the curvature be carried to the extreme limit: if the curvature be infinite, or the radius of curvature nothing: in other words, if a convex surface becomes sharpened to a point, the restraining attraction is indefinitely small; the air can no longer resist the escape of the electricity, but receives it, and itself becomes similarly electrified, exchanging some of its own electricity of the opposite kind through the same point. This exchange is carried on (fig. 36) till the pointed conductor and the surrounding air are similarly and equally electrified. Since the air can, under most circumstances, quickly come into contact with other air or solid substances to reneutralise itself, the result is an apparent loss of the electricity: in reality an absorption into the earth mass (including air), accompanied by a neutralization somewhere by the opposite kind of electricity which is invariably co-generated (Art. 25 and following).

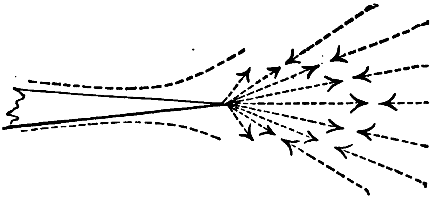
Fig. 36.

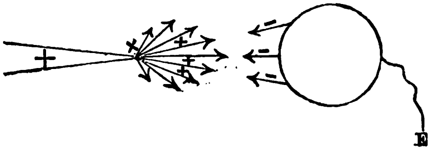

Fig. 37.

CHAPTER IV.

ELECTRICAL MACHINES.

59. We have now examined in a preliminary manner all the principles which are involved in most of the electrical machines in general use;* and as these principles may in their turn be best illustrated by means of the electricity got from such machines, the latter may now be described.

Machines for producing static electricity may be divided into two classes, frictional and inductive. The frictional machines may be considered as enlargements and perfectionings of the glass tube and amalgamed silk arrangement for obtaining electricity. The inductive may be considered, as they are indeed often called, continuous electrophoroi.

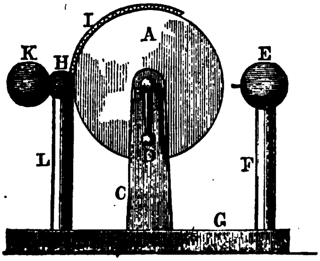

Fig. 38.

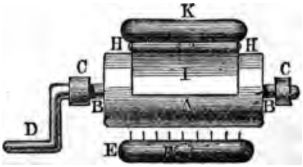

Fig. 39.

60. **The Cylinder Machine.**—The elementary parts of this machine are shown in figs. 38, 39. In fig. 38 the machine is supposed to be seen in side elevation; in fig. 39, vertically from above. The letters represent the same parts in both

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* The description of the Induction Coil, by which high tension or static electricity is obtained from a battery, will be described in Book II.

figures. A is a cylinder of thick glass, closed at both ends, and fastened to two wooden axles B, which pass through two wooden supports C, in which it can be turned by the winch D. On one side of the glass cylinder is a cylinder of brass, hollow, and having rounded ends E. This cylinder is called the "prime conductor." It is furnished with a horizontal row of sharp spikes, whose points are turned to the glass cylinder, and are about $\frac{1}{4}$ inch from it. The prime conductor is supported on a stout, well-varnished glass leg F, which is cemented into the wooden stand G. Opposite to E, on the other side of the cylinder, is a cushion covered with silk H, to which is fastened a silk flap I. The cushion is supported on a glass leg L, similar to F, and to it is fastened a hollow metal cylinder K, with rounded ends similar to E, but without spikes. The cushion is covered with mercury amalgam.*

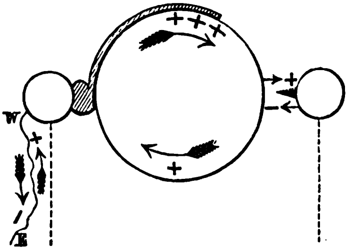

Fig. 40.

If we wish to obtain + electricity, the cushion-conductor is connected with the earth by a chain or wire. On turning the cylinder in the direction of the arrows (fig. 40), + electricity is evolved on the glass, and − on the silk. The + is carried round by the non-conducting glass until it is opposite the spikes of the prime conductor. Through the spikes + enters the prime conductor, and − leaves it. The prime conductor thus becomes +. Since this equalization takes place between a + and a neutral one, it follows that after passing the spikes the glass is still + .though not so strongly as before; in this condition it reaches the cushion. Meanwhile, the − evolved upon the cushion and flap have been conducted to the earth through the wire W. Through W, + has arrived from the earth. The result is, that neutral electricity is continually being decomposed between the flap and the glass, and this neutral is after a time derived wholly from the neutralization by the − from the prime conductor. This conductor, therefore, becomes +.

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* See Appendix, III.

If (fig. 41) the prime conductor be connected with the earth, the + electricity of the glass leaves it, and passing through the spikes reaches the earth; while − passes in the opposite direction neutralizing the electricity on the glass, which, therefore, reaches the cushion in a neutral or nearly neutral condition. Here, therefore, the result is, that − accumulates on K.

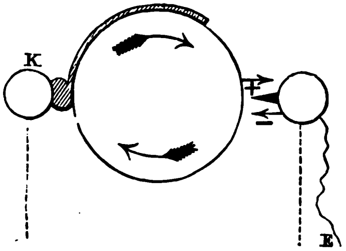


Fig. 41.

Finally, if (fig. 42) the two conductors be joined, although decomposition is continually going on, there is no free electricity manifested, for the + and − are equal in amount, and neutralise one another through the connecting wire, as the arrows indicate.

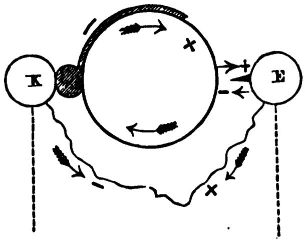


Fig. 42.

The plate machine does not differ in principle from the cylinder machine. The cushion and flap A clasp both sides of the circular plate B (fig. 43). The spikes connected with the prime conductor are arranged in two rings C, one on each side of the plate (one of these is shown by C′). The − conductor D and the + conductor E are supported on strong varnished glass legs, F and G. The axle, with its support and winch handle, are omitted in this figure. Into the prime conductor E there is fitted a mahogany rod H and ring I. In the centre of these is a metal core, which is in connection with the brass end of H, which fits into the conductor. The object of the ring and rod, I and H, is not to increase the quantity of electricity developed by the machine, but by its inductive action on the walls of the room to cause more electricity to accumulate in E, before discharge by spark takes place from E. The ring is used when we wish to get a long spark; and its employment will be better understood after Chap. V., on *Condensation.*

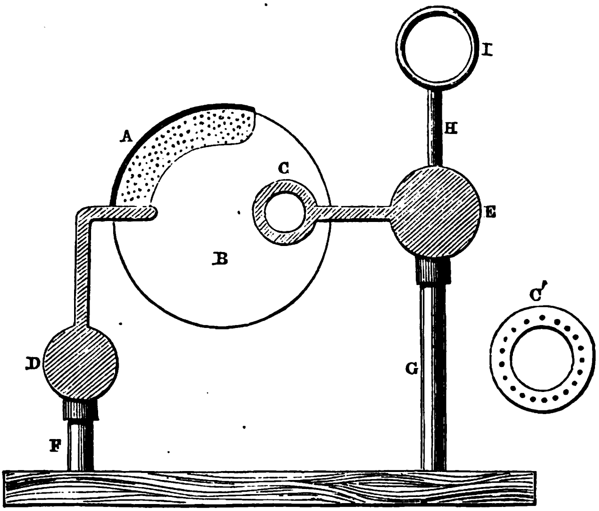


Fig. 43.

Instead of glass, use is now largely made of ebonite (a mixture of gutta-percha, caoutchouc, and sulphur), both in replacing the plate and the isolating legs. This substance, although becoming strongly – to fur and woollen, becomes strongly + to amalgamed silk. The ebonite, after a time, loses considerably its power of excitement; this may be restored by scraping its surface with glass paper. Thin sheets of ebonite, which have become distorted by heating, may be restored by pouring boiling water uniformly over them, and allowing them to cool between flat surfaces.

It is of obvious advantage that the parts of the machine turned towards the air and surrounding objects should be *free from sharp* points. Accordingly, the conductors are always rounded in form, and made as large as conveniently may be, so that the quantity of electricity accumulated may be great, and no escape into the air may take place through over tension (Art. 58).

61. Continuous Electrophoroi.—Attempts have been made with great success to employ the inductive decomposing power of a given quantity of electricity, without the labour of continually lifting and replacing the charged and chargeable plate. Machines made for this purpose are called continuous electrophori. Bertsch's continuous electrophoros is shown in fig. 44 in side elevation. A is a circular sheet of ebonite fastened upon a varnished glass axle B, which works on the brass tops of the varnished glass legs C D, and can be turned by the handle E. The leg C carries the prime conductor F, which carries towards the plate a brass arm, armed with a rake of spikes G; on the other side is a brass arm, carrying a sliding brass bar H, furnished below with a knob, and above with an isolating handle I. Opposite to G is a similar

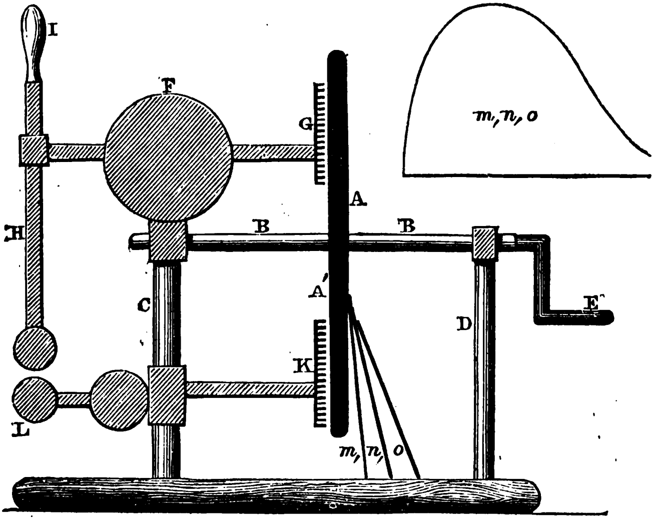


Fig. 44.

spiked rake K, which is fastened to a brass arm in contact with the ball L. Three or four sheets of ebonite, of the form shown in the side figure, are beaten on both sides with cat's skin while the handle E is being turned, and placed in succession, as shown in the figure; the first, *m*, leaning against the disc A, the second, *n*, leaning upon the first, and so on.

The action of the machine is as follows : the – electricity of *m*, *n*, and *o* inductively decomposes the electricity of L and K, repelling the – to L, and attracting the + towards K; this + passes through the points at K, and is deposited on the A′ side of AA′. It is carried round as the disc revolves, and is presented to the spikes of G, which it enters, and charges F and H + ly. At the same time – electricity leaves G, and finally partially neutralise the condition of the A′ side of the plate. The neutral electricity is again carried round to K, where it is again subjected to the inductive decomposition effected by *m*, *n*, *o*. If H and L are kept separate, the result is that + accumulates on H, and – on L, and a rapid succession of sparks passes across them. If the two are in contact a circulation of electricity is established. If H be removed from L, and L be connected with the earth, – electricity is supplied from the earth as well as from L and K, which, being deposited on A′, is carried round as before, and appears in great abundance at F. Similarly, if F and H are earth-connected, – electricity collects in L. In short, if *m*, *n*, *o*, were removed, and the spikes of K were replaced by an amalgamed silk rubber, we should have an ordinary plate machine. In Bertsch's continuous electrophoros, the action depends upon the fact, that when a non-conducting substance is moved rapidly across an electrified one, the induced electricity of the former is not kept by the inductive action close to the latter, but moves with the moving matter. In this machine, and in the one next to be described, a mechanical arrangement is employed for giving great rapidity of motion to the disc. This is the less difficult, because in such machines, unlike the cylinder and plate machines of Art. 60, friction is not essential. There is, however, in all induction machines a mechanical force required to tear asunder the unlike electricities. This is especially noticeable in the continuous electrophoros known as Holtz's machine.

62. Holtz's Induction Electrical Machine, or continual electrophoros. In fig. 45 all but the most essential parts of the machine are omitted, and the parts, for the sake of clearness, unduly separated. AA′ is a thin circular disc of varnished glass, which can be revolved perpendicular to the plane of the paper on an ebonite axle C, supported on varnished glass legs D and E. Close to AA′ is a similar, rather larger, circular varnished glass disc BB′, which has a hole in the middle for the axle of A to pass through without contact, and which is supported on isolators (not shown). At the extremities of a diameter of A (generally a horizontal one), are two spiked rakes F and G, which we will at first suppose to be connected by a wire H. Let the machine be at rest, and let there be brought opposite to F on the other side of B′, a sheet of ebonite K, which has been beaten with a cat's skin, and is therefore teeming with − electricity. This acts inductively through the plates BB′ and AA′ upon the electricity of FHG. The + being drawn to F escapes through its points and is deposited upon A′. Through G + is also drawn from A. The − of A′ enters, through F, the system FHG, and along with the − of FHG is deposited upon A. When AA′ revolves on its axle, the − of A and the + of A′, act inductively upon the stationary plate BB′,

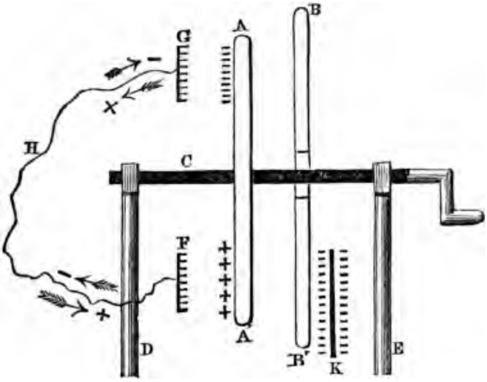


Fig. 45.

fixing themselves by this induction, and enabling themselves to travel with the plate. When the + of A′ arrives at A it enters G, when the − of A arrives at A′ it enters F. Hence there is a continual circulation of the whole of the electricity through H. Half of the moving plate is −ly, and half +ly charged. When this circulation is once established, K may be removed, for the whole of the neutral electricity has been brought under its influence. The establishment of this current is at once detected by the sudden increase in the resistance to turning which is experienced. This is due to the mechanical effort required to tear away the electricity of AA′ from the induced opposite electricity of BB′. If H is broken in the middle, when the machine is in electric action, sparks will jump across the interval; but to start with, G and F must be in contact in order that − electricity may reach A by the repulsion of K.

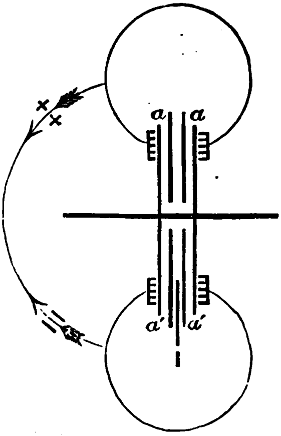


Fig. 46.

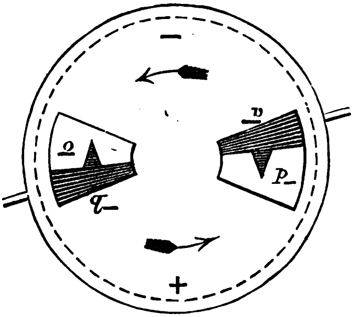


Fig. 47.

It is usual to increase the effect by doubling the number of plates (fig. 46). The rakes are then joined in pairs, and the electricity passes from one pair to the other, as is seen in the figure upon which we are supposed to be looking vertically down.

In many machines, two "windows" or holes are cut in the fixed interior pair of plates (two in each), at the extremities of the horizontal diameter, *o* and *p* (fig. 47). Bordering these holes, there are stuck on to the plate two sheets of varnished paper, *q* and *v*, provided with tongues slightly bent into the holes towards the rotating plates. The rakes in this figure are concealed, for they are situated at the back of both plates, and exactly behind the papers *q* and *v*. The excited ebonite sheet is placed upon *q* or *v* as the machine is being worked in the direction of the arrows. The object of the windows is to release the electricity which is inductively bound on the moving plate by the neighbourhood of the fixed plate; for, on approaching the window, the bound electricity on the moving plate finds no matter opposite to it, and is released, and so recharges the paper confirming its electricity. It is not found that the employment of windows and paper is of any noticeable advantage. Sheets of tin-foil may also replace the paper *q* and *v*, the windows being absent, and the foil may be electrified, in the first instance, by a spark from a jar, or even one or two charges from a proof plane. As in Bertschs' machine, so here it is essential that the plates should be turned round with considerable velocity; and for this purpose multiplying gear is used, which is behind the plate in fig. 48, which is engraved from a photograph.

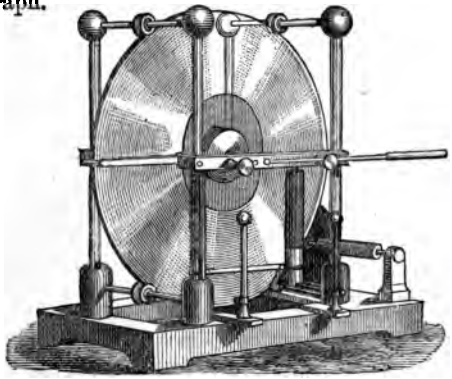


Fig. 48.

CHAPTER V.

CONDENSATION.

63. Having in Chap. IV. examined the chief means of obtaining abundance of static electricity by frictional and inductive "electrical machines," we may now assume that we have such sources at command, and return to that class of induction phenomena, which are called phenomena of condensation.

64. The induction between an electrified body and an isolated neutral one, which has been described in Chap. II., is somewhat different in its effect from the induction between an electrified body and an earth-connected one. The limitless store of neutral electricity which the "common reservoir," the earth, possesses, is in the latter case available not only to suffer decomposition, but by its decomposition to react upon the electrical state of the active body, and augment its receptive power.

65. Conceive an electrified body A (fig. 49) to be brought near to an isolated neutral one B, 1. Not only will the electricity in B tend to assume the attitude of 2, but this attitude or tendency will react upon A, bringing things into the condition of 3. This condition is clearly opposed to the tendency of the electricities in each body to recombine, and to the effort of each electricity to distribute itself uniformly over its matter.

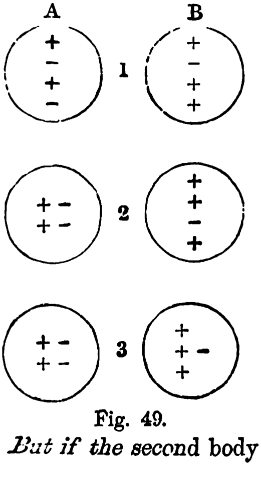


Fig. 49.

But if the second body B be in connection with the earth (fig. 50), the internal induced separation of the electricities in B is not accompanied by the strain of separation of electricity from matter. For a portion of the (say) + electricity of B may be exchanged for –, which change being effected, will react upon A, and induce further analysis of its electricity. If A at the same time be not only electrified, but in communication with a constant source of electricity, such as the conductor of a machine, – electricity will escape from A and + electricity will enter it, and, consequently, the electricity of one kind in it will be increased beyond what would have been possible if B had not been earth-connected. The charging of two masses of matter with opposite kinds of electricity, from separate sources, is, of course, still more facilitated by bringing them close together; for, in this case, even the electricity of the earth has not to be analysed.

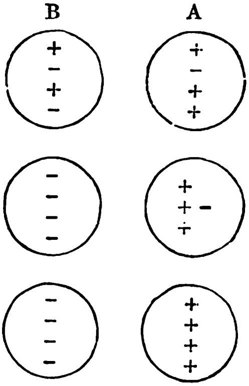


Fig. 50.

66. The electricity so accumulated from a source upon a body, by reason of that body's proximity to an earth-connected one, is said to be condensed; and the appliances used for such condensation are called "condensers." A simple form of condenser is shown in fig. 51. C is a sheet of tinfoil resting on the table, and connected by a wire G with the earth. Upon this is a sheet of varnished glass B, furnished with two loops of tape D and E; upon this, again, is a somewhat smaller sheet of foil A, which is connected by a wire with an electroscope. Repeated charges, say of + electricity from a proof plane, may be given to F or A without causing any divergence of the leaves. For it is confronted on the lower side of A by – electricity summoned from the earth through G to the upper side of C. These paralyse one another through the glass, but cannot meet on account of the isolating nature of that substance. If now the foil A be lifted, by lifting the plate B by means of D and E, the - electricity of A being no longer counteracted causes the leaves to diverge. For the same reason pieces of paper, wafers, etc., which remain at rest on A, while it is close above C, are scattered about by recriprocal repulsion when B and A are lifted.

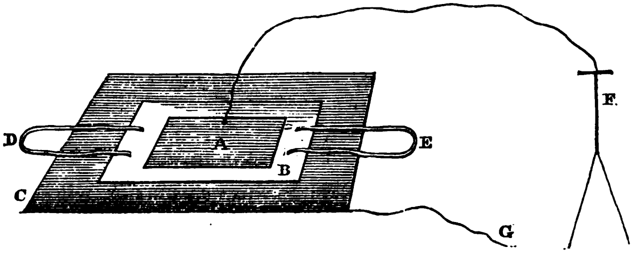


Fig. 51.

67. A more convenient form of instrument for studying the effect of induction, especially in regard to the difference in the effect, when different substances are interposed, and when the interval varies, is shown in fig. 52. A and B are two circular brass discs. A is supported by a brass leg C, B being isolated by the glass leg D. The plate A may be connected with the earth, the plate B with an electroscope F.

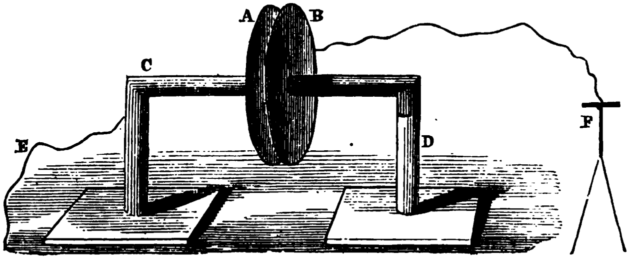


Fig. 52.

A may be moved parallel to itself. The nearer A and B are to one another, the greater the charge which B can receive *without causing* divergence in the leaves. On removing A further and further, the leaves are seen to diverge more and more; the greatest increase in the divergence for equal intervals of removal taking place when the interval is small. By this means successive small charges, each of which by itself would be insufficient to diverge the leaves, may be stored up in the plate B, while A is in its neighbourhood, and a sensible deflection of the leaves may ensue when A is finally withdrawn.

68. By means of a similar condenser, having, however, both of its discs isolated, the relation between a neutral body and an electrified one in its neighbourhood, can be conveniently studied. Thus (fig. 53), let the plates A and B be separated, and each connected with an electroscope C and D respectively. Let A C receive such a charge, say of + electricity, that the leaves of C are strongly diverged. Bring B towards A, the leaves of C will partially collapse, those of D will diverge with + electricity, but the divergence of D will never be so great as that of C. The original free + on A is partly counteracted by the − which collects on B, leaving D + ly charged. The effect cannot be so great as the cause, because the resistance of the air layer between A and B has to be overcome. On connecting D for a moment with the earth, its leaves completely collapse, and those of C partially, the first because the free + of D escapes, and is partially neutralised by the earth's − . The whole of the system D B, from being on the whole neutral, becomes thereby −. More + is summoned to A, and less is left free for the divergence of the leaves of C. If C be now connected for a moment with the earth, its leaves completely collapse, and those of D separate; for the free electricity of C is neutralised and escapes, the system C A becomes less +, less − is bound

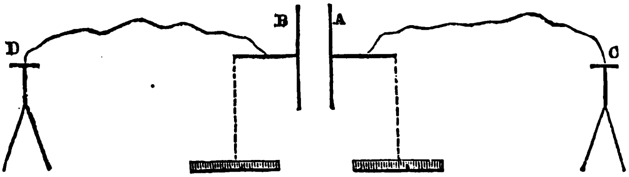


Fig. 53.

at B, and the leaves of D diverge with −. In this way a continual decreasing divergence is left in each system D B and C A, on touching them alternately. It is shown that the collapse of the leaves, on touching either electroscope, is not due to the entire neutralization of the electricity of the system to which they belong; for on removing the touched plate from the neighbourhood of the other, both systems of leaves strongly diverge.

69. The same is shown very simply by pasting sheets of tin-foil on both sides of a sheet of varnished glass, somewhat larger than they, supporting the glass vertically, and connecting both foils with electroscopes.

70. Condensing Electroscope.—The condensing plate is often attached to the electroscope, so as to form a condensing electroscope (fig. 54). In this instrument the top of the electroscope is furnished with a large circular brass disc A, varnished above and bare on its under side. The varnish is represented in the figure by a dotted line. A brass disc D of the same size as A is varnished on its lower, but bare on its upper side; it is provided with an isolating handle. By means of the varnish on the two metal surfaces they are hindered from actual contact, but they are so close to one another that induction freely ensues. We can now bring repeated small charges to the upper side of D, and during the charging touch with the finger the under side of A to release and neutralise the electricity set free by induction (which is of the same kind as that given to D). D may again receive a charge from the same source, and so on. At last H D is removed, whereupon the electricity, bound upon the upper sides of the cap, *is liberated,* and the leaves diverge with the opposite kind of

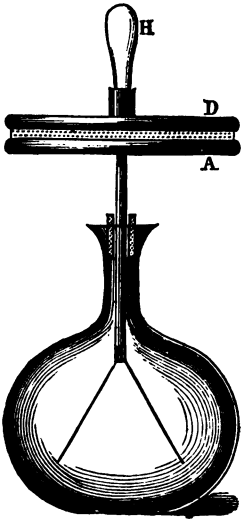


Fig. 54.

electricity to that given to D, and which is under examination.

71. When a considerable quantity of electricity has been condensed by such means as have been described, there is a great effort exercised by the two opposite kinds of electricity to unite. Each metallic surface, if isolated, may be handled with impunity as long as the neighbouring surface, charged with an equivalent of electricity of the opposite kind, is so near to the first as to hold its electricity in check. If, however, a conductor connect the two oppositely charged plates, the electricities unite in that conductor, and completely neutralise one another. The human body, chiefly by reason of its moisture (Art. 18), is a sufficient conductor to allow the electricities to pass through it. Or when one of the two bodies in opposition, containing condensed electricity, is connected with the ground, and the other is touched by the hand, neutralization takes place through the body; a spark passes between the hand and the isolated receiver of condensed electricity. The effect upon the senses is, in the case of a strong discharge, unpleasant to most people, and not easy to describe. A strong discharge of condensed electricity, or, as it is called, an electric "shock," passing through the body from hand to hand, does not produce acute pain, but gives the sensation of a sudden pulling towards the chest of some internal cords which reach to the hands.

72. For the purpose of discharging large quantities of condensed electricity, it is usual to employ a kind of tongs, the prongs of which are metal, and the handle or handles of varnished glass. The tongs are hinged where they join the glass (fig. 55) 1; or the glass handles are attached, 2, between the joint and the extremities; or 3, a thin wire or chain connects the points of a pair of tongs resembling chemical crucible tongs, but made of ebonite. The latter form is especially useful, because, without the wire, such tongs are available for lifting electrically charged bodies.

73. The appearance of a spark from a quantity of condensed electricity is different from that of an electrical machine. It is whiter, brighter, gives a louder report for the same length, and produces for the same length a vastly greater physiological effect. Moreover, it is more powerful in effecting disruption. The nature of the spark of condensed electricity may be examined by use of the condensing plane or pane. This consists of two, about equal, sheets of tin-foil pasted on opposite sides of a somewhat larger sheet of varnished glass V (fig. 56). The lower foil A has a tongue C, which is wrapped round the edge of the plate. The upper foil B has also a long tongue, which is wrapped round the varnished glass rod D. By rolling D one way or the other, B may be brought to any required distance from C. The upper foil B is connected with, say, the + conductor of a machine, the lower A with the earth.

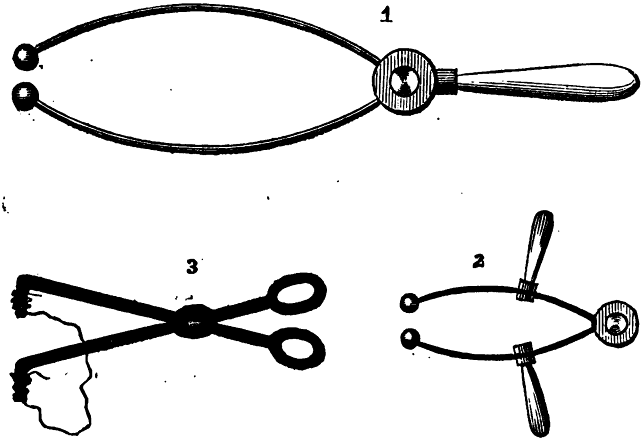


Fig. 55.

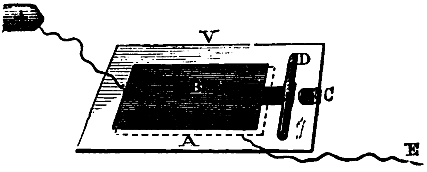


Fig. 56.

74. The **Leyden Jar** is a more convenient form of the electric pane. Its usual form is that of fig. 57: a wide-

mouthed glass jar, has tin-foil pasted smoothly inside and out, and on the bottom to within two or three inches of its shoulder; the shoulder and neck are well varnished with shell-lac varnish on the outside; the neck is fitted with a bung of baked mahogany, in the middle of this is a hole about $\frac{1}{4}$ in. in diameter; through this hole, and fastened in it by shell-lac, is a brass rod, carrying above a brass knob, and below some elastic wire, so arranged as always to press gently upon the inner coating. The outside of the jar corresponds to the lower foil of the pane of Art. 73, the inside to the upper. The knob is placed against the conductor of an electric machine, while the outer coating is connected by a wire to the earth, or simply held in the hand. If the knob be against the + conductor, that kind condenses in the inside, while − rises from the earth through the body, and condenses on the outside. If the knob be held in the hand, and the outer coating be held against the + conductor, the outer coating is charged + and the inner −. If a jar, charged in the latter way, be touched with the other hand, or placed at once, while holding the knob, on a table which is in electric connection with the body, a shock is felt, for the body then com-

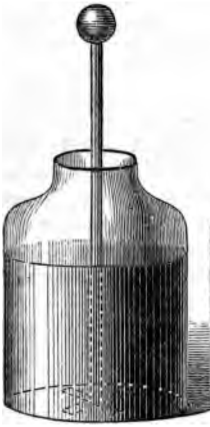


Fig. 58.

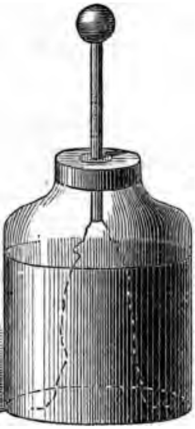


Fig. 57.

pletes the electric circuit. Such a jar may be placed on a non-conducting stand, and the hand being removed from the knob, may be applied to the outer coating, and the jar thereby moved. For some purposes the wooden bung is dispensed with, and the rod (fig. 58) supporting the knob reaches to and is fastened upon the internal foil at the bottom of the jar.

75. A convenient form of condenser, to replace the Leyden jar, may be made by laying down a long strip of vulcanized caoutchouc *a c* (fig. 59), placing upon it a narrower strip of tin-foil *b*, folding half the caoutchouc over the foil *b*, and placing another piece of foil *d*, as wide but rather shorter than *b* on the top. A rod *e*, carrying a knob is laid across the end of the compound layer; the whole is rolled up round *e*, in the direction of the arrow, and bound round with wire which is in contact with the end of *b*, this being purposely left rather longer than the other layers.

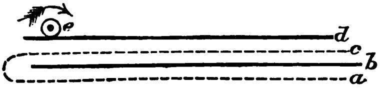


Fig 59

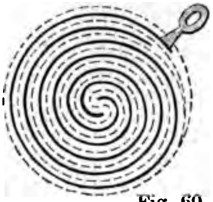
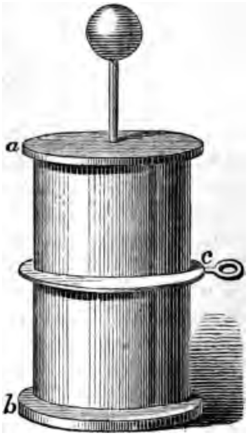


Fig. 60.



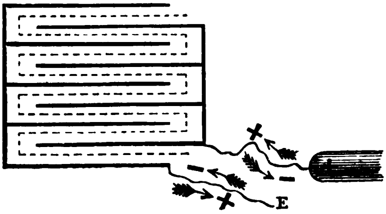


Fig. 62.

Fig. 61.

76. Another convenient form, similar to the last, is one in *which sheet ebonite* replaces the vulcanized caoutchouc of

Art. 75. A section of the jar is seen in fig. 60, where the dotted lines represent the ebonite, and the continuous ones the foil. The spiral coils are fastened between mahogany discs *a* and *b* (fig. 61), and a brass band *c* encircles the coil, and is connected by a metal pin with that foil which is not connected with the central rod. Condensers of great power and of a compact form are also made by alternating plates of varnished glass with sheets of foil, and connecting the alternate sheets of foil on both sides of the pile with one another, in a manner which is at once apparent from the sectional sketch (fig. 62), in which the dotted lines represent the glass, vulcanized caoutchouc, paper soaked in paraffin, or other isolating body. The system of foils on one side is connected with a conductor of the machine, that on the other with the earth or the other conductor of the machine.

77. That − electricity accumulates on the outer coating when the inner receives + can be proved by recourse to a modification of the experiment of Art. 66. The sheet of foil *a*, connected with the + conductor of the machine, rests upon a varnished glass plate *b*, which rests upon the foil *c*, which is connected with the earth, but lies upon the isolating stool *d*.

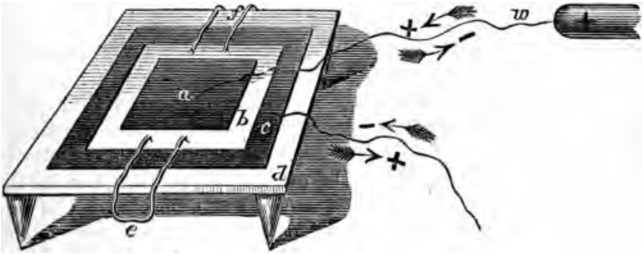


Fig. 63.

The plate *a* is charged with + and the earth wire removed. The plates *b* and *a* are lifted by means of the silk loops *e* and *f*, and completely removed. The foil *b* is then found by the proof plane to be − electrified.

Or the same may be proved as follows:—An isolated jar has its knob placed against the + conductor of a machine. An isolated metal knob is held very near to the outer coating of the jar which is being charged. Sparks pass between the knob and the jar, and the former is found to be + electrified, showing that it has lost − electricity, which has been supplied to the outer coating of the jar.

78. It is usual to suppose that the electricity of a charged jar does not reside on the surface of the foil, but rather on that of the glass in close proximity with it. This view is supposed to be proved by the following experiment with a jar with movable coatings (fig. 64). The inner coating of the jar is not pasted to the glass itself, but to a cone of wood I, which just fits the glass G. The rod carrying the knob of the inner coating I is surrounded by a little varnished glass tube *t*, so that the inner coating can be lifted without touching it electrically. The outer coating O is a conical cup of sheet tinned iron or zinc. When the pieces are together, the jar is as represented by E. In this state it can be charged as an ordinary jar. Let it be so charged and stand earth-connected on the outside. Take hold of the tube *t*, and withdraw the internal coating I; this will be found to have only a feeble charge, or none at all. Take hold of the external coating O, invert, and shake out the glass; the coating O will, of course, then be free from electricity. What has become of the charge? Reconstruct the jar in the inverse order; that is, place O over G, and invert; then, taking hold of *t*, place I in G. On connecting the knob with the outer coating, a spark *is seen* to pass almost as strong as if the jar had been left

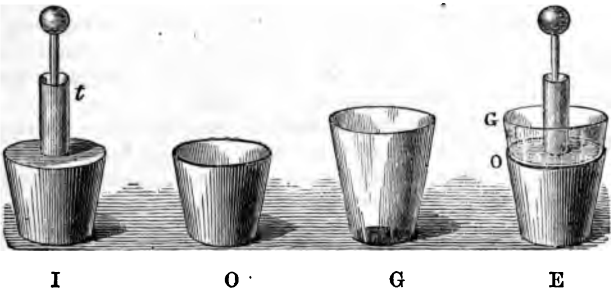


Fig. 64.

for the same time undisturbed. Or, if the charged jar be isolated and the inner coating removed as before, on laying hold of the outer coating a feeble spark is felt. The jar may be taken to pieces, as before, and reconstructed, and is found to give a spark of almost undiminished intensity. It is certain from this that, when the metallic coats are removed, the charge resides upon the surface of the glass; but this is not quite the same as asserting this to be the case when the coatings are in position.

79. Residual Charge.—If a large jar be fully charged, allowed to stand for a short time, and then discharged by the jointed discharger, it is found that a secondary though much smaller spark may be obtained on again connecting the outer and inner coatings. Again, after a time, a third still smaller spark may be got, and a fourth, or even a fifth, is sometimes obtainable. These sparks are said to arise from the "residual charge," and the residual charge itself is supposed to be owing to the power which the electricity has of penetrating, or, as it were, soaking some distance into the substance of the glass itself, each electricity being dragged towards the middle of the glass by the attraction of the opposite electricity on the opposed surface, and in spite of the tendency of each kind by itself to seek the surface. On the first discharge, the electricity which is still at the surface of the glass, and which forms always by far the largest proportion, is discharged. The electricities which have penetrated the glass from both sides are no longer so powerfully attracted; and as before they "soaked" in, so now for the most part they "ooze" out, and are ready to combine again; and so on, for the subsequent residual charges.

80. This view gains support from the fact that a spark will often pass through the glass of a jar when the jar is kept fully charged for some time, although at first it remains entire. It seems as though the soaking in of the electricity had virtually the same effect as the thinning of the glass would have; namely, the diminution of resistance to disruption.

81. Electrical Capacity of Jar.—A Leyden jar of given dimensions, that is, having its glass of a certain thickness (and kind), and the opposite foil coatings of a given area, can only receive a certain amount of charge. Let a Leyden ar have its outer coating earth-connected, and let its inner coating receive a charge of + electricity, which we will call $\overset{+}{E}$. Let the thickness and nature of the glass be such that this $\overset{+}{E}$ is able to fix $\bar{e}$ of the neutral electricity of the outer coating. Then $\bar{e} = n \overset{+}{E}$, where n is less than 1. Now the $\bar{e}$ reacts through the glass upon the $\overset{+}{E}$ in the same ratio of n, and accordingly fixes $n\,\bar{e}$ of the $\overset{+}{E}$, that is, $n^2 \overset{+}{E}$. The *free* electricity on the inside is therefore the difference between the total quantity and the fixed quantity, that is, $\overset{+}{E} - n^2 \overset{+}{E}$ or $\overset{+}{E}(1 - n^2)$, which expression we may call f. The jar is charged when f is so great that the inner coating discharges electricity as fast as it receives it; and this is soon the case when the outer coating is isolated, because then the whole of the inner electricity $\overset{+}{E}$ is free. But when the outer coating is earth-connected, $\overset{+}{E}$ must be much greater, in order that f may have reached the discharging point. Since $f = \overset{+}{E}(1 - n^2)$.

$$\overset{+}{E} = \frac{f}{1 - n^2}.$$

Thus, if the glass is of such a nature and thickness, that $n = \cdot 8$, then

$$\overset{+}{E} = 2{\cdot}8\,f.$$

82. An electrical battery consists of a number of Leyden jars having all their outer coatings connected together and earth-connected, and all their inner coatings also connected together, and in communication with the conductor of a machine (fig 65). If all the outer coatings have free earth communication, such a series of jars or battery acts like one jar, whose two coatings are of the sizes, respectively, of the sum of the inner and outer coatings of the separate jars. And in this arrangement, which is the one most frequently used, adopting the notation of Art. 81, $\bar{e} = n \overset{+}{E}$, provided that the glass is alike in nature and thickness in each jar.

83. Sometimes the jars are so placed and connected as to form what is called the "cascade" arrangement (fig. 66).

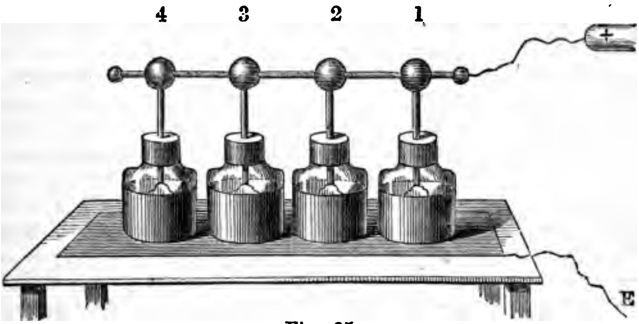


Fig. 65.

Jars 1, 2, and 3, are isolated by being placed on a sheet of vulcanized caoutchouc or other means. The inside of 1 is connected with, say, the + conductor, the outside of 1 is connected with the inside of 2, the outside of 2 with the inside of 3, the outside of 3 with the inside of 4, and the outside of 4, which is not isolated, is connected with the earth. The + electricity which enters 1 fixes and is partially fixed by + electricity on the outside of 1; this liberates + for the inside of 2, which induces – on the outside of 2,

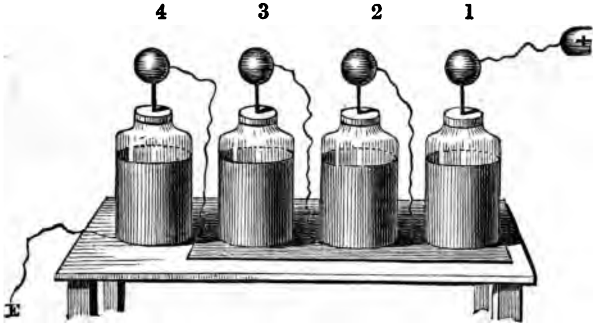


Fig. 66.

liberating + for the inside of 3. The + in 3 induces – on the outside of 3, which liberates + for the inside of 4. The + in 4 finally decomposes the earth's electricity, the – of which collects on the outside of 4. By this method of charging, all the jars become similarly charged, and there is a certain economy of labour. For the second jar is charged, as it were, by the waste electricity of the first, and so on. And if the outer coating of the last be connected with the inner of the first, a spark of considerable power will pass. Or if the jars be disconnected by the isolating tongs, and their outer coatings connected and their inner coatings connected, the battery is charged in the ordinary way; but though more rapidly effected, the charge cannot be so great as when the battery is charged in the ordinary way; for induction has to take place through as many thicknesses of glass as there are jars. The jars are found to be nearly equally charged.

84. The Unit Jar.—The unit jar is employed for measuring the charge which is introduced into a jar. In fig. 67,

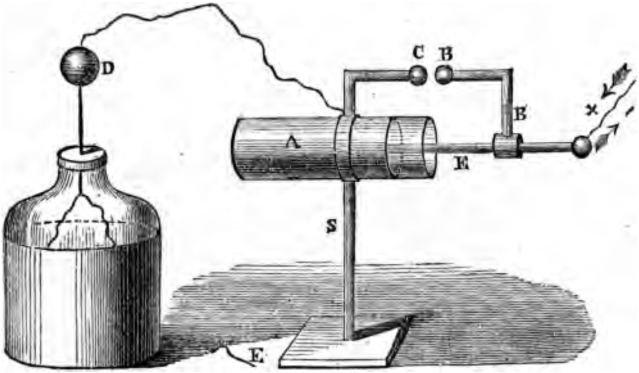


Fig. 67.

A is a little Leyden jar supported horizontally on a varnished glass stem S. Its outer coating is in contact with a fixed knob C. The inner coating is in contact with a horizontal rod E, which is in connection with the conductor of the machine. E also carries an arm B, which slides over E in such a way that the knob B may be brought as near as we please to C. The rod of knob C is in connection with the inner coating of the jar which has to be charged, and whose outer coating is connected with the earth. As the inner coating of A acquires, say, + electricity, its outer becomes –. This causes the inside of D to be +, the corresponding – on the outside of D being derived from the earth. This accumulation of + electricity in D goes on until A gets so charged that a spark breaks through the interval between C and B. The – of C is at that instant nearly neutralised, and the jar D is left + ly charged to an amount depending upon the previous accumulation of electricity in its interior, which is dependent on and varies with the distance between C and B. The unit jar is very useful for charging another jar equally at different times, for the jar is charged to the same amount when the same number of sparks has passed between B and C. But the intensity of the charge is not strictly proportional to the number of sparks, because the tension throughout changes as the jar gets charged.

CHAPTER VI.

ELECTRICAL DISCHARGE.

85. WE have seen that an electrified body may influence another body, whether electrified or not, in two ways. If both be surrounded by air, they act and react through the air in such a manner that the effects of induction are produced. If one being neutral, the other is strongly charged; or if they be strongly charged with opposite electricities, or if they be brought, in either case, very near to one another, a flash of light is seen and a sound heard. And these phenomena may vary in intensity from an almost invisible spark and a noise not louder than the tick of a watch, to the brilliancy of a flash of lightning and the loudness of a thunder-clap. Conceiving a + electrified body surrounded by air, and in indefinite space, we may imagine the surrounding air to be subjected to a kind of electrical strain or tension, the – being attracted, and the + repelled, but *the two* seeking to recombine 1 (fig. 68). The same takes

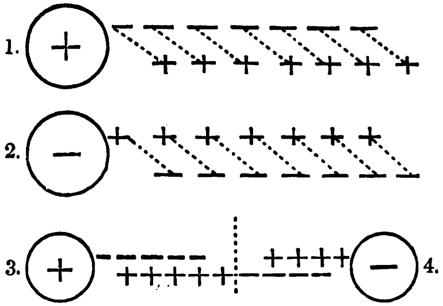


Fig. 68.

place with a – electrified body 2. The relation of attraction between dissimilarly, and repulsion between similarly electrified bodies, may be referred in kind to that of the extreme inductively influenced air molecules. Considering the + body 3 holds – bound and liberates +, the – body 4 does just the reverse. The unbound + at the end of the 3 series unites with the unbound – at the end of the 4 series. By this release, the condition of tension of each series is destroyed; more – is drawn towards 3, and more + thrust away; more + is drawn towards 4, and more – thrust away. A continual neutralization takes place in the region between 3 and 4. The nearer the bodies are together, the greater the tension of each series which is relieved. Hence the bodies 3 and 4 approach one another, for a reason closely analogous with that which causes two suspended planes of glass to approach one another when hung side by side in water. In the latter case, we have a release of the water raised by capillarity between the planes; in the former a release of tension on the sides nearest to one another, and allows the tension on the off sides to prevail. The force required to separate electrically attracting bodies is expended in redecomposing their interlocked electricities.

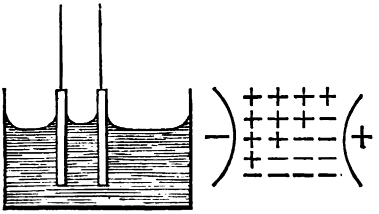


Fig. 69.

86. When the oppositely electrified bodies approach within a certain distance, the uncompensated tensions of the electricities become so great that the equilibrium of the air is destroyed, and the electricities neutralise one another by air motion. There seems to be a greater attachment or cohesion between matter and +, than between matter and – electricity, as will frequently appear in the sequel. Consequently, although we may suppose an equal motion of the electricites in the discharge, yet the + is accompanied by matter, both that of the surrounding air and of the solid of which the + ly charged body is composed. Referring to fig. 68, we may suppose the dotted lines linking the inductively-separated elements together to be ruptured, the + pours into 4, the − into 3, and if the quantity of + in 3 is equal to the quantity of − in 4, perfect neutrality results.

87. **The Spark.**—It is not difficult to understand how such violent molecular disturbance sets up that molecular vibration which is called heat, and how this, in its intensity, communicates vibration to æther, producing light. The condition of the "dielectric," or substance through which the influence is exercised, is similar when only one body is electrified, the other being neutral. But the second can never be so strongly electrified as the first, because the first only influences the second by dint of polarizing the dielectric, which is work expended.

88. The spark appears in most cases single, and to travel from the + to the − electrified body. This is probably due to the fact above mentioned, that the + electricity carries incandescent matter with it, which renders its passage visible, and because the stronger light produced near the + conductor produces a quicker impression on the retina. We may consider a spark to be the series of phenomena attending the destructive decomposition of the electricity of the dielectric, and the combination of its elements with oppositely electrified bodies. Without matter there is no light. The spark has different forms. When it takes place between closely neighbouring bodies, it is apparently straight (fig. 70). At a somewhat greater distance the path becomes zig-zag (fig. 71).

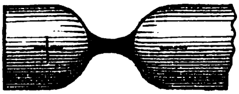


Fig. 70.

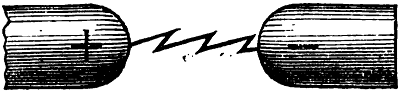


Fig. 71.

The departure from the straight line appears to depend upon the accidental want of uniformity in the air, owing to dust-particles, and inequality in moisture and temperature. For though the conductors remain rigidly in the same places, the image of the spark on the retina is never twice alike. At a greater distance the spark often presents the appearance of branching. The main trunk in such cases being on the + side (fig. 72).

With regard to the colour of the spark, it is found to depend upon the nature of the substances between which the spark passes (chiefly on that of the + side), and upon the nature of the gas or vapour through which the spark travels.

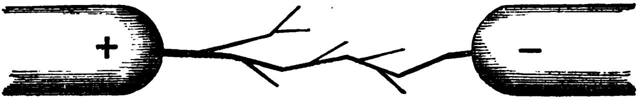


Fig. 72.

The first affects chiefly the region of the + pole, the latter affects generally the intervening space. The description of the various colours of vapours and gases rendered thus incandescent by the passage of the spark, belongs rather to the science of light. It may here be mentioned, however, that so constant and trustworthy are the luminous manifestations under constant conditions, that by comparing the spectra of different metals, when they form poles of high tension electricity, means are obtained for determining the qualitative, and, in come cases, the quantitative, composition of alloys; and by comparing the spectra of electrically incandescent gases with those of the sun and stars, a clue is obtained to the chemical nature of the ærial constituents of those luminaries.

89. Other Forms of Discharge.—The nature of the discharge is also affected by the size or rather degree of curvature of the surfaces from which it occurs. Thus (fig. 73), if

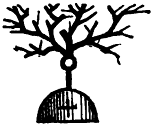


Fig. 73.

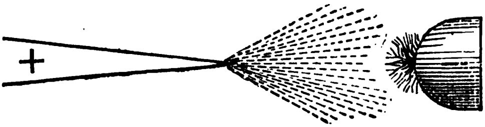


Fig. 74.

a metal sphere $\frac{1}{8}$ in. in diameter be fastened to the + conductor of a powerful machine, the discharge assumes the form of a brush or pollard bush. On still further decreasing the radius of curvature of the + conductor, until it becomes a point, the + electricity escapes without possessing visible structure in the form of a glow. The − body in the neighbourhood acquires a small star-like spot of light (fig. 74). When the conductor of a machine is armed with a point, the accumulation of electricity on that point is so great that the air itself receives + electricity, supplying –, and the body is discharged (compare Art. 58). The whole air of a dry room may be thus charged with + or – electricity by connecting one or other conductor with the earth, and arming the other with a point.

That the air itself becomes electrical when surrounding an electrified point, is shown (fig. 75) by holding the flame of a candle near to a point attached to the + conductor. The flame is blown away. If the candle be placed upon the conductor, and an earth-connected point be presented to it (fig. 76), it is also blown away. In fig. 75, the air receiving + from the point also becomes +, and repels the similarly electrified point, causing what is called the electric wind. In fig. 76 the air about the point becomes – and repels the – ly induced point. In fig. 77, metal wires are arranged like the spokes of a wheel, the nave of which is a metal cap. The metal spokes are pointed and bent all in one direction at their ends in a horizontal plane. The whole is supported on a pointed support standing on the conductor of the machine. The extremities of the wire spokes becoming +, discharge that electricity into the air, which, therefore, becoming + repels the spokes, and drives them all round in the direction indicated by the arrows. This instrument is called the electric wheel.

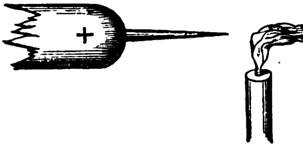


Fig. 75.

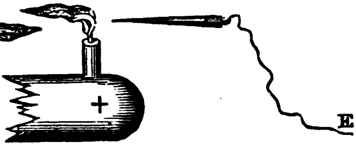


Fig. 76.

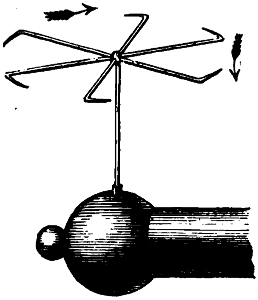


Fig. 77.

90. Relation of Heat to Discharge.—It appears that as discharge produces heat by the agitation of molecules, so heat promotes discharge. The vibration of the molecules of a metal may be so increased by heat that neither the metal itself, nor the air in its immediate neighbourhood, can maintain the strain or electric tension proper to an electricant or dielectric. The degree of heat necessary for the manifestation of such effects is, with metals, that known as incandescence; that is, heat so intense as to be accompanied by light. This relation may be exhibited in a variety of ways. Fig. 78 represents an ebonite pen-holder armed with a copper hook, by means of which a hot iron ball may be held in a state of isolation. When at a bright white heat, the iron ball refuses to receive, or at least to retain, even for a moment, a charge of either + or – electricity. On cooling down, but while still of a red heat, it acquires the power of receiving a – but not a + charge; and this distinction is maintained through a considerable range of temperature. At a lower temperature yet, but still at a dull red heat, the ball begins to be able to receive + electricity, and shortly after, as it cools, it accepts both kinds with nearly equal readiness. If we conceive the air-bathed and electrically air-straining masses of iron, 1 and 2 (fig. 79), to be respectively + ly and – ly electrified, and then to be gradually heated, the air which we have already partly seen (Art. 86) to have a greater attachment to + than to – electricity, will, supposing the attachment between the metal and both kinds to be equally diminished, succeed first, in the molecular turmoil at the heated surface, in carrying away the +.

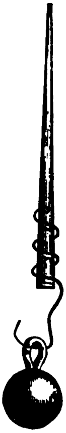


Fig. 78.

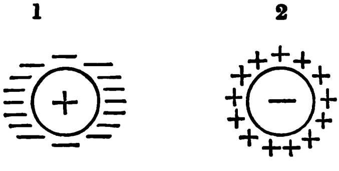


Fig. 79.

91. Again, if we take two equally-charged gold leaf electroscopes (fig. 80), 1 with + and 2 with – electricity, and if we bring earth-connected white-hot iron balls a few inches above the caps of each, they will be discharged with nearly the same facility. On repeating the experiment continually, as the balls cool, it is found that 1, or the + ly charged electroscope, ceases to be discharged, though the ball is of a red heat, while 2, or the – electroscope continues to be immediately discharged, although the ball has lost all incandescence. This effect, which might at first sight seem to be opposite of that of Art. 90, is, in truth, based upon exactly the same relation. The charged electroscopes polarise or strain the air, as is shown in the figure No. 1. The polarised dielectric air induces – on the earth-connected ball above it; No. 2 induces +, so that we have the hot balls of 2 and 1, of fig. 80, in exactly the same predicament in regard to the surrounding air as the balls 1 and 2 of Art. 90 (fig. 79) respectively. The discharge in the second series of experiments (those of this Art.) does not commence at the actively electrified body, but from the inductively electrified one. But the discharge or release of strain is communicated through the dielectric air to the electrified body.

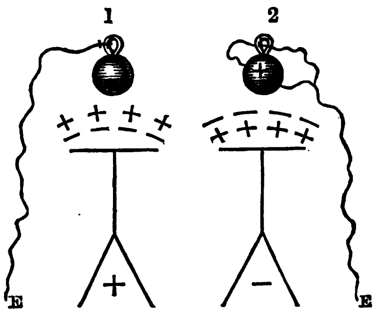


Fig. 80.

If the hot balls of Art. 91 are replaced by isolated ones at the same temperature, the discharging power is in all cases more feeble, and the difference exhibited between the + and – electricities is far less marked; because both + and – then exist in the same ball, although partially separated by induction, and the difference of the effects becomes dependent upon the difference of the distances of the two induced electricities from the electroscope, which again depends upon the size of the balls. There is also a tendency of the two electricities to recombine. The same power of discharge enjoyed by hot metals can also be shown by replacing the iron balls by platinum wires, rendered incandescent by a galvanic current. Fig. 81 shows an electroscope and a Leyden jar being discharged in this manner. Thin platinum spirals are fastened to the exposed ends of a gutta-percha covered copper wire, the other ends being in each case connected with a galvanic battery. The outer coating of the jar is connected with the earth to allow the − to escape as the + is discharged. The discharge of a jar depends, in the first instance, on the discharge of the free electricity in the inside (Art. 81)—

$$(f = \overset{+}{E}(1 - n_2))$$

which releases its proportion of − electricity on the outside, which results in the freeing of some more internal electricity, and so on. An isolated jar can be discharged if similar hot wires are placed at equal distances, one near the inner, the other near the outer coating.

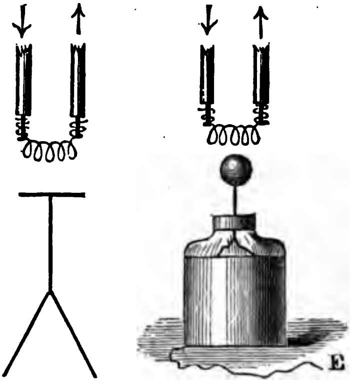


Fig. 81.

92. The power enjoyed by hot bodies of discharging electricity is not proportional to the quantity of heat which the discharging body gives out, or the electrified body receives; for a large sheet of iron at 100° C. may give out an indefinitely greater amount of heat in the same time than a few inches of incandescent platinum wire, although the latter be white hot. The former may shed, when at the same disdance from the electroscope as the latter, a much greater quantity of heat upon it, and yet the iron at 100° C. has no similar discharging effect, while the latter has an immediate and complete effect. And this is quite in accordance with the assertion of Arts. 90 and 91, that the origin of the discharge is the surface of the hot body, and not the surface of the electrified one; and that the discharge is due to the violence of the molecular vibration of the hot body, and of the air touching it, and is not to be produced by more multitudinous vibrations of lesser velocity and greater amplitude.

93. Further, it may be shown that the source of heat must itself be the induced matter; for an electrified jar or electroscope is not discharged when, by a lens, the heat of the sun is intensely concentrated on it; nor when it is in one focus of a pair of conjugate spherical reflectors and the source of heat in the other, although in both these cases the electrified body receives far more heat than it does when it suffers discharge by the approach of a hot body. Finally, if the charged electroscope and an earth-connected cold body in its immediate neighbourhood be surrounded by air, through which heat is being radiated, as that from the sun concentrated by a lens, no discharge ensues. The molecules of the diathermanous air are not in vibration, though the æther in which they are enjellied is so.

It need scarcely be added that a white-hot ball in connection with an electroscope prevents the electroscope being charged with electricity of either kind; and as the ball gradually cools it permits the electroscope to be charged with –, and afterwards with + electricity.

94. With regard to the temperatures at which the difference of behaviour of + and – electricities towards a discharging body are most marked, it appears, from thermometric determinations, effected by measuring the heating of a given weight of water, when a given weight of metal at the critical temperature is plunged into it, that when an earth-connected mass of iron is of, or above, such a temperature, that 1 gram. of it, on cooling to 0° C., gives out about 140 heat units (1 gram. water 1°C.), the iron will freely discharge both kinds of electricity when two or three inches from a charged electroscope. When 1 gram. of iron cooled to 0° C. gives out about 116 heat units, + electricity just ceases to be discharged, while – is discharged freely. When 1 gram. of the iron on cooling to 0° C. gives out only 84, and under, heat units, neither electricities are dischargeable.

95. Discharges by Flame.—The discharging and collecting powers of flames are intimately connected with the discharging power of white-hot metals. If the flame of any burning body be connected electrically with a charged body, the latter soon loses its electricity. And this is sometimes attributed to the particles of the burning gas acting as removers of electricity. That this is not the case appears from the consideration that the removal of a portion of an electrified body, although diminishing the total quantity of electricity left, does by no means invariably diminish its tension. It is generally considered that the particles of the vapour or gas act like a multitudinous collection of points, affording egress to electricity of one kind, and ingress to that of the other. That this is not the case is shown by placing a gas burner, fed by a vulcanized caoutchouc or other non-conducting tube, on the top of an electroscope, and charging the latter. On turning on the gas no discharge ensues, but on lighting it the discharge is immediate and complete. The true cause of the discharge effected by flame is doubtless the release of the strain of induction by the thermal agitation of the molecules, and this relief is effected in the first instance at the flame itself. This is shown by holding a flame above, and disconnected with, a charged jar or electroscope; whether the flame be about a body earth-connected or isolated, the discharge is very rapid. Thus (fig. 83) the ebonite penholder, with the hook at the end, is clothed in cotton wool and dipped

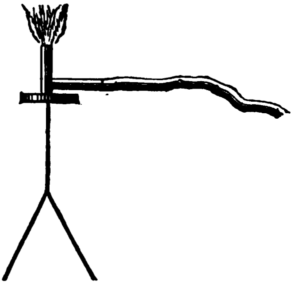


Fig. 82.

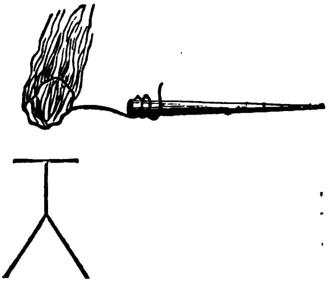


Fig. 83.

into ether, alcohol, benzol, or bisulphide of carbon, which is then ignited and held a few inches above a + ly or − ly charged electroscope or jar. The leaves immediately collapse, although none of the products of combustion reach the electrified body, and although the heat which is radiated to it is very trifling. Upward air currents, it is true, are established about the electroscope; but comparative experiments in which hot or cold air is blown from a bellows upon a charged electroscope without discharging it, show that such currents are impotent. The feebly luminous flames of alcohol and bisulphide of carbon, in neither of which is there, at any place, solid matter, are as powerful discharges as are the flames of ether and benzol, the former of which is luminous, and the latter charged with unburnt and discombined carbon. A flame in the neighbourhood of an electrically charged body must therefore not merely be looked on as a region where chemical affinity is the consequence and cause of heat motion, but also as the place where heat motion is the cause as well as the effect of electric discharge. In other words, just as heat causes bodies to recompose, and as the recomposition of bodies gives rise to heat, so heat causes the electricities to combine, and their combination gives rise to heat. And not only are these relations similar, but, as will appear more fully in considering voltaic electricity, they are probably linked together by the fact that chemical union is the result, as the cause, of electric neutralization.

96. Discharge by Evaporation.—A metallic cup of water placed on the top of an electroscope prevents the electroscope from retaining for more than a few seconds a charge of − electricity, while it exerts a scarcely perceptible influence on the retention of a + charge. A lump of melting ice in a basin on the electroscope acts in a similar way. The + electricity is in both cases freely discharged if an earth-connected white-hot iron ball, a flame, or a piece of incandescent coke, be held over the water at a few inches distance. The spontaneous discharge of − electricity, in preference to +, from a wet surface, may be looked on in the same light as its discharge from a dry surface by a neighbouring hot body, and especially as its discharge by flame. In the latter case, heat *passes by* radiation from the dielectric to the electrified body;

in the former, such heat is similarly derived by the electrified body as heat of vaporization. In the case of discharge by evaporation, the loss of heat by the dielectric, and its gain by the water, takes place at the actual surface of the water, and hence, and on account of the great specific heat of aqueous vapour, comes the great amount of electrical discharge for a comparatively feeble range of temperature difference.

CHAPTER VII.

EFFECT OF DISCHARGE.

97. Distribution on Non-Conductors.—The point discharge may be used for distributing electricity on non-conducting surfaces. Thus the sheets of ebonite in the continuous electrophoros of Arts. 61 or 62, may be held over a point in connection with the – conductor of a machine, in order to become saturated with – electricity. The inside of a varnished glass may be held over a similar point, and acquire so large a charge of electricity, that when (fig. 84) it is placed over a number of pith balls, resting on a metal plate in contact with the earth, the balls commence dancing, and continue doing so for a long time. Their electricities are inductively decomposed by that of the glass. They rise against gravity till they reach some point of the glass, when they receive a charge similar to that of the neighbouring glass, and are repelled. The opposite kind of electricity, which collected on the outside of the glass through the body while the glass was being charged, does not undergo release by the action of the balls, and gradually neutralises the effect of the nearer but continually diminishing interior charge. On releasing the outer electricity by stroking the outside of the glass with the hand, the activity of the balls is reinvigorated.

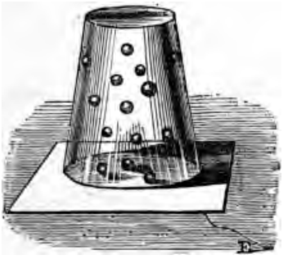


Fig. 84.

98. Lichtenberg's Figures.—The distribution of electricity of either kind on a non-conducting surface is well exhibited in Lichtenberg's figures (fig. 85). A cake of resin, or a sheet of varnished glass, or ebonite, is beaten with fur till it becomes strongly and uniformly − electric. A + ly charged Leyden jar is held with its knob downwards, and the knob is made to trace any arbitrary figures on the surface. A crackling noise is heard as the knob passes over the − surface, discharging it at and about the points of contact, and recharging it then with + electricity. A mixture of finely-powdered red lead and sulphur is shaken through a muslin bag from some height above the cake. By friction with the muslin and with the sulphur, the red lead becomes + electrified; by friction with the muslin and with the red lead, the sulphur becomes −. The red lead, therefore, as it falls seeks out the − portions of the plate, and is chiefly deposited upon them; the sulphur seeks out the + parts, that is, the parts at and near where the knob touched the cake. The result is a curious ramified structure of yellow sulphur on a back ground of red lead.

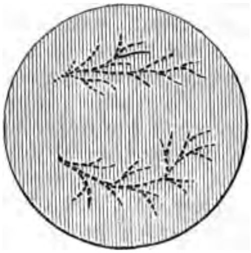


Fig. 85.

99. Penetrative Effect.—The most noticeable penetrative effects of electricity are those exhibited by lightning, which will be briefly considered in Chap. IX. A jar, whose coatings are out of proportion large compared with the thickness of the glass, will be penetrated by a spark between the two coatings; the penetration is usually in the form of a round hole, which, of course, renders the jar useless. A piece of cardboard, fastened between the two knobs of the discharger when a battery is discharged, is found to be penetrated by a hole, whose edges are frayed in such a manner as to suggest the passage of matter from the interior outwards both ways. A sheet of writing paper, in like manner, being held between the knobs of Holtz's machine, becomes perforated by the passage of

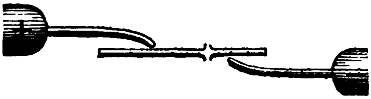


Fig. 86.

each spark. If (fig. 86) the + and − conducting bodies from which the spark passes are separated by a card in such a way as not to be exactly opposite to one another, the card is penetrated opposite the − pole. If, however, the air in which the discharge takes place is somewhat rarefied, the hole approaches the middle between the poles.

The penetrating power of a spark depends more upon the intensity of the *free* electricity than upon the total quantity. Accordingly, the spark from a machine, such as Holtz's, may readily have more penetrating power than the discharge from a jar, especially if the latter has thin glass. For experiments of penetration it is necessary that the discharging knobs or points should be especially well isolated.

100. Heat Effect.—The intense light which accompanies electrical discharge is evidence of the extreme heat which thereby prevails, since it is not the electricity which is visible, but the incandescent gas; and since, for gases to be luminous, they require an intense heat. A gas burner connected with the earth is placed near the prime conductor of a machine, if the edges of the burner are not too sharp, the spark ignites the gas. Or, if placed on the machine, an earth-connected knob near it will ignite the gas. A little cotton wool placed in a cup, and moistened with ether or alcohol, will be ignited when the knob of a charged Leyden jar is brought down upon it. The knob of the electrophoros is fastened to an isolated brass knob, held a little above a gas jet. On placing the plate of the electrophoros on its cake − passes to the earth from, and + from the earth to, the plate; this spark ignites the gas. On lifting the plate the electricities pass in the opposite direction, and the extinguished gas may again be lighted. Or, if a powerfully excited glass rod be brought near to an isolated conductor, whose further end is close to an open gas jet, the + repelled electricity of the conductor in springing over the opening will ignite the gas. On removing the glass rod the − passes to the earth, and the + again re-enters the conductor, thereby again igniting the gas.

101. The heating effect of an electric discharge is much increased by introducing into the circuit some considerable resistance. It seems doubtful by what means this increased effect is produced, for it occurs far away from the interposed resistance. Heat effects, as well as those of disruption, are often conveniently studied by means of the "universal discharger" (fig. 87). This consists of a little table *a*, which can be raised or lowered by means of the screw *b*. Two glass legs *c* and *d* support tubes *e* and *f* on hinges. Through these tubes pass the discharging rods *g*, *h*. If *g*, as in the figure, be connected with the earth, and the two points *i* and *j* brought to within an eighth of an inch of one another on the table, and their points covered with a pinch of gunpowder, we may pass a spark from the jar *k* by means of the jointed discharger *e* to *h*, and so to the earth through the powder, without igniting the powder but only scattering it. But if a piece of wet string, about 8 in. long, connects *h* and *e*, then, as soon as a spark is drawn from the jar, the simultaneous spark across *i* and *j* ignites the powder. And this same enhanced heating effect is produced if the wet string is brought in between *g* and the ground.

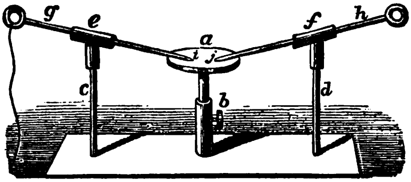


Fig. 87.

102. The heat of the spark can be, but only roughly, measured by the air expansion produced in its passage through a given quantity of air in a chamber (fig. 88). The spark leaps across the interval *a*, *b* between the brass knobs in the glass cylinder *c*, the lower part of which is in communication with a side tube *d*. The main tube *c* and the side tube are partially filled with water, so that the side tube serves, by the rise of the water in it when the spark passes, as a guage to indicate the expansion of the air in *c*.

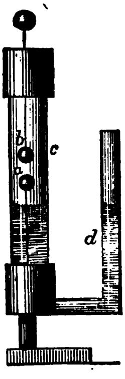


Fig. 88.

103. The electric spark has heat sufficient to determine the union of chlorine with hydrogen, or oxygen with hydrogen or hydrocarbons, and is of great use for this latter purpose in the chemical analysis of gases in "eudiometers." Thus a mixture of oxygen and coal gas are enclosed over mercury in a tube, of which the top only is shown in fig. 89, through the sides of which two platinum wires B and C have been fused, and bent so as nearly to meet. On joining, say, B to the earth, and connecting C with the knob of the electroscope, or that of a charged jar, a spark passes between B and C, and if there be sufficient oxygen present, the whole of the free and combined hydrogen is oxidized to water, and the whole of the carbon to carbonic acid.

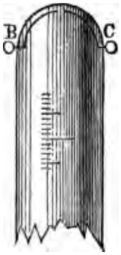


Fig. 89.

Toy cannons and pistols are made, whose action depends upon the sudden expansion of the aqueous vapour which is produced when oxygen and hydrogen are made to combine by means of the electric spark.

104. When a strong discharge is made to traverse an imperfect conductor other than air, heat is also produced. In the case of metals, which are not disintegrated by the strength of the discharge, the heating effect can be measured. Fig. 90 shows one means of measurement. A platinum spiral of thin wire connects the two knobs *a* and *b*. The spiral is in a glass globe *f*, which is air-tight, but carries below a narrow tube *d*, reaching to a vessel of water *e*. The water stands some distance up *d*. The expansion of the air in *f*, caused by the heating of the wire *c*, produces a corresponding depression of the water in *d*.

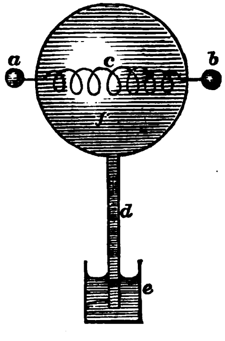


Fig. 90.

105. The sudden expansion of water through which a spark passes is so considerable, and the water is so incompressible, that unless the water be very free to expand, the vessel holding it is frequently shattered. Fig. 91 represents an arrangement, which need not be further described, for passing a spark through water between two copper wires in a glass tube. The tube is generally shattered into slender spiral triangular splinters, whose apices are near the interval over which the spark passes.

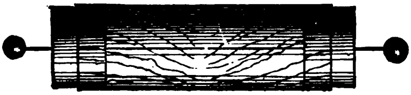


Fig. 91.

The disruptive effect of a spark from a battery of some power may be well shown by making the charge pass through a thin piece of gold, platinum, or silver wire, stretched over a sheet of cardboard. The wire is fused and volatilized, and driven into the cardboard, where it condenses into a characteristic streak.

106. Light Effect.—The luminous effect of electricity in passing through various gases variously rarefied will be more fully considered in Book II., where it will be shown how to procure a yet more abundant and constant source of static electricity by means of voltaic electricity. It is easy by exhausting a tube, into the ends of which platinum wires are fused, to obtain a partial vacuum of several feet in length. If the exhaustion is carried further and further, it is found that the tube may be made longer and longer, and will still allow the electricity to pass through. The discharge, however, assumes the form of a glow pervading the tube uniformly from end to end, and assuming a blue violet colour. The whole aspect reminds us of the aurora, and this natural phenomenon is, indeed, most plausibly attributed to a closely analogous cause. If the vacuum be made still more perfect by filling the tube repeatedly with carbonic acid, and exhausting and finally absorbing the residual carbonic acid with potash, the spark refuses to pass across an interval of even the tenth of an inch.

The luminous appearance in the vacuum of the barometer, when the mercury is agitated in the dark, and which is caused by the friction between the mercury and the glass, also illustrates the passage of electricity through imperfect vacua.

Various substances, especially such as are capable of "insolation," that is, which absorb light and give it out with or without change of colour, are especially susceptible of being made phosphorescent by the electric light. Water, sugar, paper, but especially the sulphides of the alkaline earths, glow for some time after they have transmitted a spark. In the case of quartz the glow changes from a red to a white as it fades off.

107. Magnetic Effect.—If (fig. 92) a non-magnetic steel needle N S, be laid upon and across a strip of tin-foil, and if a series of sparks, or a continuous stream of electricity, be sent from the prime conductor through the foil to the earth, the needle, after a time, is found to be magnetic, and have poles as in the figure. The polarity of the needle is destroyed and ultimately reversed, if, the + electricity passing in the same direction, the foil is placed above the needle, or if (being below) it passes in the opposite direction. If both alterations are made, the needle has the polarity of the figure. One can understand from this experiment how the polarity of a ship's compass needle may be thus destroyed or reversed by the passage across it, above or below, of the immense spark discharge of lightning.

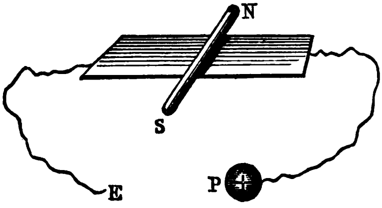


Fig. 92.

108. If an exceedingly long and thin copper wire, covered with silk or other non-conducting material, is wrapped into a coil, in the midst of which is a delicately suspended magnetic needle, whose polarity is counterbalanced, as far as the directive magnetism of the earth is concerned, by being associated with a similar needle above the coil of equal and opposite polarity, the needle will turn round if the continuous stream of electricity from the prime conductor is poured into the earth through the copper wire, and, indeed, in such a way that if the + current passes beneath the needle from its south to its north end, the north end of the needle will turn to the right of an observer who looks down upon both needle and current. It will turn in the opposite direction if the + current passes in the opposite direction. The arrangement is shown in fig. 93. The arrangement of such a pair of compensating needles and the coil will be more fully described in Book II.

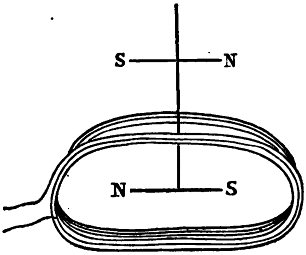


Fig. 93.

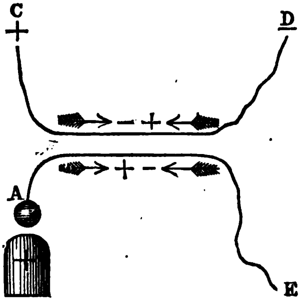


Fig. 94.

109. Effect of Discharge on Neighbouring Conductor: Induced Spark.—In fig. 94, a wire A E carries a knob A, which recieves a spark from the prime conductor, and conducts it to the earth: let C D be a closely neighbouring wire. As each spark passes in A E in the direction indicated by the arrows, C becomes for the instant + and D −. If C and D be brought very near to one another, a spark will cross the interval between them as often as the discharge takes place through A E. The spark between C and D is called the induced spark, and it is seen that, in regard to the parts of the two wires which are near to one another, the passage of + electricity and of − electricity is the opposite in the second (or secondary) to what it is in the first (or primary). With single wires thus placed side by side the momentary current around the secondary is scarcely perceptible. To increase the effect both primary and secondary may be rolled into flat spirals covered with some isolating substance, and placed close together in such a fashion that, starting from the centre of each, and travelling along the wire to the circumferences, two points remain close neighbours (fig. 95). Then, if the break in the secondary be closed by a thin piece of platinum wire, the wire becomes red hot by the secondary discharge, and may ignite gun cotton with which it is in contact. The secondary discharge itself may cause a discharge in a third neighbouring wire, which is therefore called a tertiary; and as this is in the opposite direction to the secondary, it is in the same direction as the primary. If, therefore, the three wires are closely juxtaposed, the primary would excite a current in the tertiary by direct influence in the opposite direction to that which it would cause through the intermediation of the secondary. Accordingly, to obtain a tertiary an arrangement is made (fig. 96) by which the secondary is broken into two parts one of which is receptive from the primary, the other is active towards the tertiary. In the figure, B and C are both parts of the secondary, A being the primary. D is the tertiary, and the spark passes between *e* and *f*. In this way sparks of the fourth and fifth orders have been obtained.

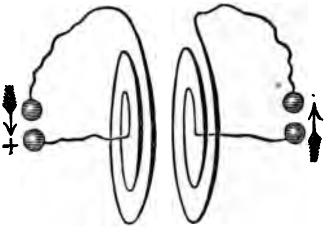


Fig. 95.

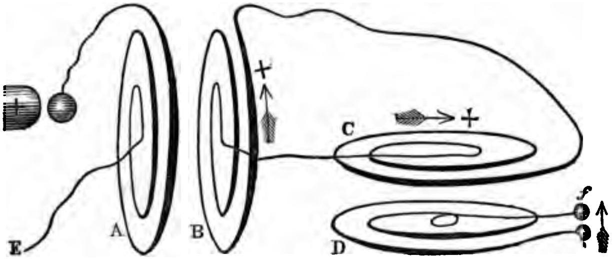


Fig. 96.

110. Duration of Spark.—Although, on account of the very general phosphorescence of bodies, a body which has been illuminated in the dark for an instant by any means really continues to be visible after the source of light is *extinguished,* yet such phosphorescence is so feeble that it does not interfere with the examination of the extent of duration of the spark. It is a well-known fact that the effect of a momentary flash of light on the retina produces an impression which endures for some time, and it does not matter for our present purpose whether the continuousness of the effect be due to a continuousness of a physical effect upon the retina, or to a continuousness of impression on the brain. Thus, a quickly-moving point of light produces the impression of a line of light. The separate effects are blended. So, a rapidly-revolving white disc with a black section appears to be uniformly grey. Such a disc, however rapidly it may be revolving, in a dark room appears, when illuminated by the light of the electric spark, to be still; that is, the section is seen to be sharply defined. If it had moved an appreciable distance while the spark endured, its edges must have appeared bleared and its general width greater.

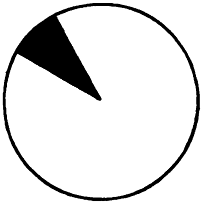


Fig. 97.

Velocity of Discharge.—The merely momentary nature of the duration of the light accompanying the discharge is intimately connected with the rapidity of the rate at which electricity travels. If a number of fragments of tin-foil are pasted on a glass so as nearly to touch one another, and a spark be sent from one end of the series to the other, all the intermediate spaces are, as far as the eye can judge, simultaneously illuminated by sparks of light; so that any device traced out by the interstices becomes legible. Further, if several miles of isolated wire are arranged so as to have one end near to an earth-connected ball, and the other near to a charged jar, the instant the spark passes between the jar and one end of the wire, a spark passes between the other end of the wire and the earth. Further, if the wire be broken in the middle, the spark springs across the middle breach, as far as the unassisted judgment can tell, at the same instant as it passes across either extreme breach. But the assisted judgment judges differently; for if (fig. 98) we bring the three points where the + spark 1 enters, 2 passes the middle breach, and 3 leaves the wire, of several miles in length; and if we receive the light from these three points upon a rapidly revolving plane mirror A, it is clear that if there be the slightest difference in the time of occurrence of the sparks, the mirror will have advanced a little in its rotation between the occurrence of the earlier and later spark; and in consequence of this, the reflections of the three sparks will no longer form a straight line. It is found that when the mirror moves with an immense velocity the reflections of the sparks are neither spots of light, nor are they all three in a straight line. They are seen as short lines, as represented in the figure by *a*, *b*, *c*. If the extreme intervals are in a horizontal straight line, so are their reflections; but the reflection of the centre spark is not in the same straight line, but so out of it as to indicate that the impression of the spark of the central breach was produced after the impression of the extreme sparks, and that these latter were produced simultaneously. The drawing out of the impressions into lines, of course, shows that the spark has some endurance. The displacement of the middle spark-impression shows that the discharges enter both ends of the wire simultaneously, and meets in the middle, and that some time is occupied in travelling from either end of the wire to the middle. From the rate of rotation of the mirror, and the apparent displacement of the central spark, we can, knowing the length of the wire, calculate the velocity of the discharge. It is found to vary according to the resistance of the wire and its surroundings. It may, however, travel at the rate of one or two hundred *thousand miles a* second.

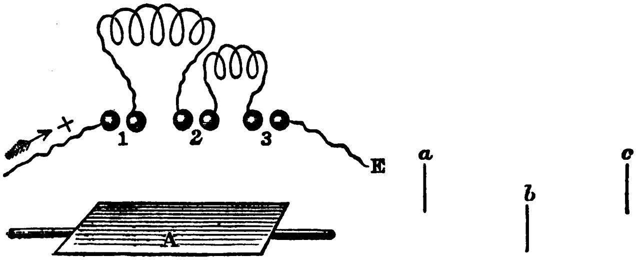


Fig. 98.

CHAPTER VIII.

DIELECTRICS.

111. We have hitherto considered induction in the same light as we are accustomed to consider gravity, namely, as acting through space from body to body, and although not hindered by the interposition of gaseous matter, yet not dependent upon the presence of such matter for its effect. On the other hand, we have considered the induction which takes place through one or more conductors as being the result of the successive decompositions of their electricities. If substances which, like air, are imperfect conductors, be they solid, liquid, or gaseous, are interposed between one electrified body and another, the electrical effect which passes through them is found to vary in amount with the nature of the bodies. Such bodies are called dielectrics. The power which they have of permitting induction to pass through them is called their inductive capacity, and the ratio of the inductive capacity of a body to the inductive capacity of air is called its specific inductive capacity. The most perfect isolaters are, as a rule, those bodies which have the greatest specific inductive capacities. In order to avoid induction round the dielectric instead of through it, the arrangement of fig. 99 was used in the few experiments which have been made in this direction of research. A and B are two hollow metal hemispheres which fit together

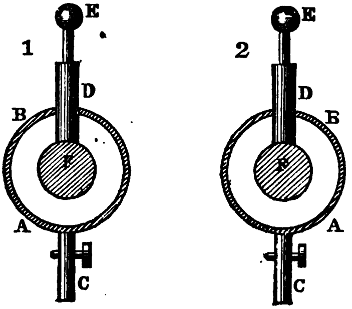


Fig. 99.

closely at their joint equator. Below is a tube C, which can be screwed on to the air-pump plate, and is furnished with a tap. Above is a wide tube D, which is filled with shell-lac. Through the midst of the shell-lac passes a brass rod, which carries above a little knob E, and below a metal sphere F, concentric with the compound spherical shell. The space between the sphere F and the shell A B can be exhausted to any required extent, or it can be heated to any temperature, or it can be filled with any non-conducting substance, solid, liquid, or gaseous, whose specific inductive capacity we wish to determine. The specific inductive capacity is directly determined by using two such instruments, the one containing air, and the other the substance under examination. These two, 1 and 2, must be precisely alike, and that they are so is seen by comparing the inductive capacity of the two when both contain the same substance—say air. This is done as follows. The knob of 1, and therefore F, receives a charge, say, of +, from the prime conductor, while A B is connected with the earth. The whole becomes charged as a Leyden jar, of which the glass is replaced by air. The tension of the electricity is measured by touching the knob of 1 with a proof-plane, and conveying the charge to the knob of a torsion balance, which is described in Chap. X., Art. 136. If now the knob of 1 is made to touch the knob of 2, the outer coatings of both being earth-connected, and if it is found then that the free electricity of each is the same, and half that of the first when it alone was charged, we know that the two instruments are perfectly alike. The amount of free electricity is inversely proportional to the inductive capacity, other things being the same. Accordingly, if 2 be filled with some other dielectric, say sulphur, while 1 is filled with air; and if 1 is so charged that the tension of its free electricity is measured by a torsion *t*, and if after touching the knob of 2 the tension of 1 is found to be less than half *t*, more than half the electricity has entered 2. But on testing the knob of 2, we again find less than half *t* of free electricity. Accordingly, the electricity which has entered 2, has been more completely inductively neutralised by the – earth electricity than that of 1, or sulphur is a better dielectric than air.

Measured in this way, the following numbers have been obtained :—

Air at all temperatures and tensions,	1
Glass,	1·9
Shell-lac,	2·0
Sulphur,	2·24

Other gases, simple and compound, have also the specific inductive capacity 1. That induction takes place more readily through shell-lac or sulphur than through air, can be readily shown by sliding a thick cake of these substances between the top of an electroscope and an electrified and isolated metal ball, which is above the electroscope and inductively diverging its leaves. The leaves are then seen to diverge still further.

112. Although a dielectric may readily allow the inductive effect to pass through itself, yet its own electricity may undergo comparatively slow inductive decomposition. Thus (fig. 100), a charged ball A is hung from a silk thread on one side of an ebonite plate B, which can revolve; on the other side is a brass ball D, in connection with the electroscope C. Induction immediately ensues, but gradually falls, the leaves collapsing. If the plate be turned until a fresh part of it interposes, the leaves again diverge, and this may be repeated a number of times. It is only slowly that the + so separates itself from the + of the disc as to be able to neutralise the sphere inductively, and so diminish its action through the disc. So that, if (fig. 101) the dotted lines of 1 represent the normal condition of the electric tension, both + and – , the dotted lines of 2 represent the conditions of the electricity after the electrified sphere has acted for some time.

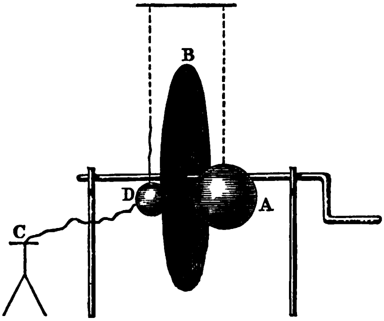


Fig. 100.

113. The condition of a body through which induction is taking place, is supposed to be exhibited by the following experiment: Numerous fibres of silk are immersed in pure turpentol. Two metal knobs, one connected with the earth, the other with one of the conductors of a machine, are plunged beneath the surface of the liquid. The fibres arrange themselves from pole to pole, joining one another end to end. The experiment appears to show that induction in this case is not a superficial action, but even in this respect the evidence is not quite conclusive.

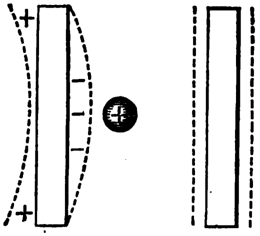


Fig. 101.

CHAPTER IX.

OTHER SOURCES THAN FRICTION.

114. Pyro-electricity.—In Chapter I., Art. 29, a few other means beside friction were mentioned, by which static electricity can be developed. A few such instances may be examined in this chapter. Certain crystals, when being heated, acquire a distinct electrical polarity, that is, one region of the crystal becomes + electrical, the opposite region –. In every case where this happens, exactly the opposite polar condition is established as the crystal cools. Tourmaline (essentially a borosilicate of magnesium and aluminum) is of a rhombohedral form. It is most generally found as little crystalline prismatic rods, the central line of which may be called the crystalline axis. The crystals are in section (perpendicular to the axis) triangular, with the angles of the triangles replaced by more obtuse angles, so that the prism has nine faces (fig. 102). The ends of the crystal are

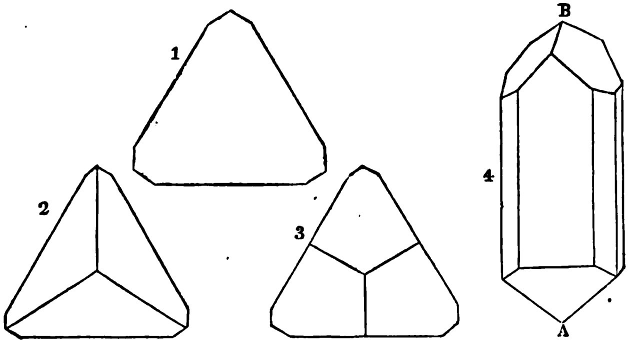


Fig. 102.

each formed by three faces of the rhombohedron. But while at one end of the crystal the intersections of these faces pass through the three prominent edges of the crystal (2), at the other they fall upon the centres of the three prominent faces (3), the whole aspect of the crystal being as 4. Such a crystal on being heated, provided its temperature to begin with is not below 10° C., becomes + electrical at the end A or 2, and – at the end B or 3. This polarity continues while the crystal is being heated up to about 150° C. If the rise in the temperature is arrested, the crystal immediately loses its polarity, at whatever temperature it may then be. On beginning to cool, it becomes again electrical, but with reversed polarity, B or 3 then becoming + and A or 2 –. Such polarity as before is at once lost, if the change of temperature is stopped. The end A is sometimes called the *analogous* pole, for there the rise in temperature co-exists with + (both the same sign). The pole B is the antilogous pole, for there the gain of heat corresponds with – electricity. The polarity of the tourmaline may be shown by hanging it and heating it over a hot plate; or, better, by wrapping each end in a separate piece of platinum wire, which is stiff enough to support the crystal, and connecting the wires with the two poles of the electrometer described in Art. 136.

Sugar, boracite (borate of magnesium), also show electrical polarity when being heated, and the opposite kind when being cooled; and, as in the case of tourmaline, the polarity is related to the crystalline form, and especially to the attitude of the terminal facettes. There is no doubt that pyro-electricity may be excited in a great number of crystals, but the exhibition is less marked than in these three.

115. Pressure Electricity.—If two perfectly similar bodies are pressed together and separated, it is clear that neither of them can exhibit electrical excitement. For electric excitement being electric decomposition, there can be no reason why one body should become + rather than the other. But whenever two bodies, which differ only in temperature, are pressed together, they are found on separation to be so electrified that the originally cooler body has become +, the hotter –. And this is in accord with what we have already seen, and what we shall examine further in Book II., that heat and + electricity move together. It is of course necessary for the development and examination of the static electricity produced by the pressure between bodies, that one at least of them should be a non-conductor.

If a piece of cork is pressed against caoutchouc, coal, amber, shell-lac, zinc, copper, silver, or hot calcareous spar, it becomes + ly electric, the substances named becoming –. The cork becomes – ly electric after pressure upon dry fur, flannel, skin, etc., also with sulphate of barium, sulphate of calcium, fluor spar, and cold calcareous spar.

The greater the pressure with which bodies are pressed together, the greater the amount of electricity found on them after separation. The separation according to planes of crystalline cleavage of parts of a crystal, also gives rise to electric phenomena. Hence, possibly, the luminosity observed when crystals are formed [the crystallization of arsenious acid out of a hydrochloric acid solution (the recombination of the arsenic from chlorine to oxygen)], and also the light apparent when crystals of sugar, quartz, etc., are rubbed together.

The overcoming of the cohesion when sheets of mica are split, is also accompanied by the electrification of both laminæ, one + ly the other – ly. And in this case the electrical polarity is restored when the halves are again pressed together and separated. The relation of the polarity to the attitude of the plane of cleavage to the crystal faces, has, in this case, as far as I know, not been examined.

116. Electricity of Evaporation. — Perfectly pure water does not become electrical on evaporation; but if it contains free oxides of the alkaline metals, or alkaline earth metals (oxides of potassium, sodium, calcium, barium, etc.), the water becomes + during its evaporation, the vapour becoming –. When water, which contains any soluble acid or carbonate, sulphate, chloride, nitrate or acetate, is evaporated, the water and its containing vessel becomes –, the vapour +. It is owing, in the opinion of many, to the relationship between the vapour and residual water, when such salt solutions evaporate, that the electricity of the air is to be attributed (see Art. 118).

When water evaporates under pressure greater than one atmosphere, the quantity of electricity developed increases with the pressure, but in no case does it appear unless the water contain some of the above salts in solution. A boiler which has been much used, and in which there is a deposit of "fur" (carbonate and sulphate of lime, oxide of iron, etc.), may have its electrical polarity reversed, the steam becoming − and the boiler +. Such a boiler cleaned and washed out with caustic potash or soda, again yields + steam.

Attempts have been made to utilise the electricity of steam, as a source of electricity, in place of the ordinary machines, and it is found that the action of such instruments depends greatly upon the friction encountered by the escaping steam. Accordingly, in the hydro-electric machine, high pressure is employed, and the orifice through which the steam escapes is constricted. Fig. 103 shows one of the steam nozzles in section. In the figure, *c* represents a projecting sheet of brass in the steam pipe, and *d d* a lining of hard wood in the nozzle, which increases the effect of the friction in producing electricity. In fig. 104 a number of such nozzles are seen side by side; the steam from them passes between two metal combs *f f*, which are connected to the earth, and which remove the + electricity of the steam. The boiler, which stands on glass legs, acquires thereby − electricity, and furnishes an abundance of long sparks.

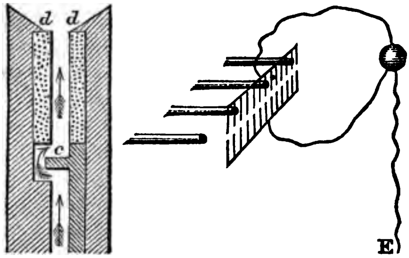


Fig. 103.

117. Electricity of Chemical Change.—The consideration of this source of electricity belongs generally to Book II., where chemical change will be considered as giving rise to dynamic electricity, and thence to static electricity. A few *instances may* here be given, in which static electricity is an immediate consequence of chemical change. A mixture of chlorine and air, passed through a copper tube, causes the tube to become –, the air itself becoming +. A piece of carbon connected with the condenser of an electroscope, and ignited, exhibits – electricity. Germinating plants also become –.

118. Atmospheric Electricity.—There can be no doubt that the more ordinary kinds of atmospheric electricity or lightning are perfectly identical with the frictional electricity we have been hitherto examining. But the cause of atmospheric electricity is still a matter for investigation. It is supposed by many that the evaporation of the chloride – and sulphate – containing sea water, and, indeed, so-called fresh water as well, is the prime cause of the air's electricity; and there is no doubt that, as regards quantity, the cause would be adequate to the effect. In a serene sky, moreover, the atmospheric electricity is almost always +. If, however, the electricity of the clouds engaged in the turmoil of a violent thunderstorm be examined, some of the clouds are found to be + and others –. Now although, as far as I know, no experiments have been made to prove it, we might almost assume, by analogy, that when neutral vapour of water partly condensed, the condensed part would be –, the uncondensed +. Fresh vapour we know to be +, and hence violent motions of attraction and repulsion. Vegetation has been regarded by some as a prime source of the atmospheric electricity. But electric storms arise so far out at sea, that we must consider the electricity of vegetation not essential. Judging again wholly by analogy, there can be but little doubt that when two unequally heated currents of air encounter one another, the colder must become +, the warmer – electrical. If the latter be moist, the vapour condensed in it, by contact with the colder current, will also be –.

119. The nature of the electricity which exists in the air, or in clouds, is determined by raising some long and pointed conductor, such as a sharply pointed copper wire, to the sky, and isolating it. The lower end may then be tested, and its electricity will be the same as that about the raised point. When the air is so much charged with electricity as that there is danger of a spark passing from the lower end to the earth, the two are connected together. A paper kite, flown by a wet string, or one in which a thin copper wire is inwoven, also seems to gather the atmospheric electricity. In such a case the lower end of the string must be fastened to a dry silk cord to isolate it from the hand. In meteorological observatories, the collector is usually a flame at the end of a conducting rod penetrating the atmosphere. The flame collects better even than a multitude of fine metallic points. Another means of causing a body to assume the electrical condition of the surrounding air is to connect it with a cistern otherwise isolated, and to allow water to drop continually from the cistern. In whatever condition the water in the cistern may be at first, in regard to the surrounding air, the two soon become alike; for the drops, as they form, increase the collective surface of the liquid, and therefore weaken the electricity on it. On falling, they thus remove electricity.

120. If we imagine two equal drops of water charged with electricity of the same kind to be brought by any means to coalesce, the resulting drop must have twice as much electricity as its constituent drops had; but the surface of the collective drop is not so much as twice that of each constituent drop, consequently the collective drop is overcharged. Whatever causes electrified drops of water to grow by adhesion of other equally electrified drops, must bring the condition of charge higher. Perhaps it is for this reason that a downpour of rain generally quickly follows a flash of lightning during a thunderstorm.

121. The most favourable point from which to view lightning is the top of a lofty hill, when the lightning clouds are beneath. The flashes are then seen to pass from cloud to cloud, and generally to reach the earth more rarely: at once suggesting to the observer that, in the most violent storms, the total quantity of – is about equal to that of + electricity. From such a point of view, also having known objects as a background, the length of the lightning flashes may be approximately measured, and found to be often miles in length. The thunder, of course, corresponds to the tick, clap, or smack of the artificial electric spark. The air is suddenly rarefied and dispersed in the course of the lightning, and rushes together again after the discharge has passed. The air is thus disturbed for a length perhaps of miles simultaneously, or nearly so. The sound travels at, say, 1100 feet per second, and will take four or five seconds to travel a mile. Accordingly, if the hearer is a mile further from one end of a flash of lightning than from the other, there will be four or five seconds between the beginning and ending of the thunder, supposing the sound not to be protracted by echo. Or, again, by counting the seconds between the visible flash and the audible thunder, we get a measure of the distance of the nearest point of the discharge.

122. The heat of the lightning is often sufficient to set fire to houses and dry trees; it seeks the readiest conductor to the earth. It melts metallic conductors if they are insufficiently thick. Less perfect ones it scatters, forcing them to convey the electricity. It enters the ground, and sometimes fuses sand into the form of siliceous tubes. On exposed planes it seeks out the most prominent object, moving or stationary. They who seek shelter from a thunderstorm beneath a tree, invite destruction; for the lightning, entering the lofty branches, meets with resistance in its passage down the trunk, and will divide, so that a portion will pass through the better conducting body.

123. The Return or Back Stroke.—In most cases, when a stroke of lightning proves fatal, it is by the direct passage of + electricity into the body, and − out. If a man be imperfectly isolated, he gradually becomes charged with − electricity when a + charged cloud is hovering over him. If this cloud be suddenly discharged by a flash between it and any other object, the man finds himself suddenly loaded with −, which, owing to his imperfect contact with the earth, cannot at once escape by the way it came. Consequently, − electricity leaves the man, and + enters him from the earth in the form of what is called a return stroke, which may knock him down. If a man be very perfectly isolated, the neutral electricity of his body may be inductively decomposed by the neighbourhood of a charged cloud. When such a cloud is discharged, the electricities in the man's body recombine, and a considerable shock is felt, though, like the return shock, this is seldom or never fatal.

124. The inductive charging of the earth's surface with −

electricity beneath a + ly charged atmosphere, is often seen to result in the existence of a brush or point discharge of − electricity. Thus the masts of ships, the bayonets of soldiers, the very fingers of the outstretched hand, are sometimes seen to glow with a discharge of − electricity, exhibiting what is sometimes called St. Elmo's fire.

125. Lightning Conductors.—Buildings and ships are frequently furnished with lightning conductors, which consist of thick metal rods projecting several feet above the object to be defended, sharpened above into one or more points, and connected below with some good conductor, in good or abundant connection with the earth. A ship is thus protected by carrying a copper rod down the main-mast, and connecting it with the copper sheathing of the ship. A lightning rod, used to protect a building, may have its lower end connected with the service of water pipes, or, failing these, it may be led into a well or pit full of charcoal. It is not the proper function of a lightning conductor to convey to the earth an electric discharge which may strike the building to which the conductor is attached; but to prevent such a discharge from occurring, to exhaust the electricity of the cloud by, as it were, tapping it, and to throw into it electricity from the earth of the opposite kind. A lightning conductor is said to protect a region around its base, whose diameter is twice the height of the point of the conductor from the ground.

126. The difference in colour of lightning discharge appears to depend wholly upon the degree of moisture in the air, and to the height above the earth at which the spark passes. There are, however, many well authenticated instances of lightning assuming another form, and one which at present cannot be imitated by artificial means. It appears in some cases as "fire balls," or masses of light of great intensity, which move with a comparatively low velocity. Such meteors, which may properly be called thunderbolts, appear to avoid contact with the earth, and usually cease their existence with an explosion, from which no solid matter reaches the earth. Such phenomena are rare, and are so threatening and portentious, that the observers of them are seldom in a *condition* to give very trustworthy descriptions of them.

CHAPTER X.

ELECTRICAL MEASUREMENT—POTENTIAL.

127. Unit of Electricity.—Static electricity is generally measured by its mechanical effect in producing attraction or repulsion. Let us imagine two indefinitely small bodies, both + ly and equally electrified, at the distance of 1 meter from each other. They repel one another with a certain force which may be represented by a weight, say, fractions of a gram. We might adopt as electrical unit that electrical quantity, which, existing in the two bodies, produces a repulsion of $\frac{1}{n}$ gram. Instead of employing the actual force thus measured by weight, it is usual to express the force by taking the velocity which the force, acting for a unit of time on a unit of mass, would give to that mass. Each of two equally charged bodies is said to have a unit of electricity, if, when at a distance of 1 centimeter from one another, the one will repel the other with a force which in 1 second of time would impart a velocity of 1 centimeter a second to 1 gram of matter.

128. If we conceive a uniformly charged conductor to shrink in size, the total quantity of electricity on it will remain the same, but there will be a greater number of electric units per unit-area than before: the electricity has become "denser" or of a higher "tension." If a small jar be charged, it may give a shock sufficiently powerful to be extremely disagreeable; but if the charged jar be connected outside and in with a large empty jar, the shock from the two produces a much less painful effect, although the discharge appears equally instantaneous as before, and the same quantity of electricity passes. So in Art. 57, in examining the distribution of electricity on irregularly shaped conductors, we have found them to be a greater quantity of electricity at those points where the curvature is greatest. We likened the electricity to an atmosphere of varying depth, and because there is no evidence of the existence of an electric atmosphere, we likened the state to that of tension, density, or elasticity, which would result from the superincumbent pressure of an aërial atmosphere of varying depths.

Imagine the earth and its air to be at rest in space, and free from all influences beyond their own gravitation. The air would then be at rest upon the face of the water; it would thinly clothe the lofty mountains, and densify itself in deep mines. In the latter, its density, elasticity, tension, would be greater than on the former; but there is universal rest: for the greater tension is produced by the greater pressure. Let us suppose now that we take a rigid cubic foot vacuum, and bring it in succession to the various parts of the atmosphere, there open it, close it, and remove it: we would get more air from the depths than from the summits. The rigid vacuum is the proof plane of the electrical experiments of distribution; or again, conceive such an atmosphere to be probed by a rigid vacuum tube of infinite length, one end of which is opened at different depths, and imagine the vacuum to be kept constantly perfect. Wherever the open end of the tube were placed, the whole of the atmosphere would ultimately pass through it. The vacuum tube is the earth-connected wire of the electrical experiments.

If a mass of dense air were suddenly exposed on the top of a mountain, or a mass of rarefied air at the bottom of a mine, the whole atmosphere would be disturbed.

In cases of aërial or electrical distribution resulting in unequal tension, there is no resulting tendency to motion, for there is no motion.

129. Potential.—If we lift a kilogram a meter in height on to the top of a pedestal, and there let it rest, we have done an amount of work which we may call a kilogrameter. An indefinitely small touch may topple it off, and it will, just before reaching the ground, have acquired a momentum which is equal to the work done in lifting it. By lifting the kilogram against gravity, we have therefore stored up work in it much in the same way as if we had elongated a *spiral spring,* whose lower end is fastened to the earth, and hooked the upper end to a hook a meter above the ground. The work which the kilogram is capable of doing, by dint of its momentum on reaching the earth, is equal to the work done in lifting it. The work which a raised body is capable of doing, if it fell a certain distance, is called the *potential* work of the body, or simply, its (mechanical) potential. It is clear that potential is relative, depending upon the attraction between the earth and the body, and though the mass of the body be constant, the potential will vary with the distance between the two; that is, from what level above the earth the kilogram is raised a meter.

130. Instead of a unit of weight, let us take a unit of electricity, which was defined in Art. 127. Let us take the electrical condition of the earth as 0, or neutral, just as we considered the body in Art. 129 to have no height. The work done by the unit of electricity, in moving from its place to the earth (not necessarily descending), is the unit of potential. The electrical potential of a body is the mechanical work which the electricity of the body is capable of doing in passing to the earth, or other indefinitely great reservoir of electricity of the same kind as the earth's. Two bodies have different potentials when work is done by the electricity of the one of higher potential moving towards that of the lower. Potential may be defined as the preparedness to do work. If we force two similarly electrified bodies towards one another, and hook them near together, or if we separate two dissimilarly electrified bodies and prop them apart, we do mechanical work, just as when we compress a spring, or separate the kilogram and the earth; and the work they do in resuming their portion is in all cases equal to the work we have spent.

131. It follows from the above, that all conductors in connection with one another are in the same state as regards their electrical potential, however different the tensions may may be upon them; for if there were any difference of electrical potential, electrical motion would ensue. Accordingly, when the inside of a Leyden jar is charged, the outer coating, being earth-connected, maintains its potential always constant, namely, that of the earth or 0; there is no tendency to motion. On working a frictional machine, the prime conductor acquires a higher potential than the earth; and what we have hitherto considered the – of the rubber, we may now regard as being simply electricity of a lower potential than that of the earth. The potential between the prime conductor and the rubber conductor, supposing them both insulated, is the sum of the potential of both referred to the earth. Just as the difference of temperature between + 20° C. and – 20° C. is 40° C., in which the temperature of freezing water represents the electrical potential of the earth, and is taken arbitrarily as zero.

132. Measurement: Electrometers.—From what has been said, it follows that electrical potentials, or rather their differences, can be measured in work units; and since quantity of work is independent of the time in which it was done, we may refer potential to the unit electric force, namely (Art. 127), that quantity of electricity with which, if two indefinitely small bodies at the distance of 1 centimeter are charged, they will repel one another with a force which will, in one second, produce on a gram a velocity of 1 centimeter a second. Taking in the equation $v = ft$, at the end of 1 second $v = 5$ meters, we have the static force corresponding ·002 grams, which, acting on a gram for 1 second, would give it a velocity of 1 centimeter a second.

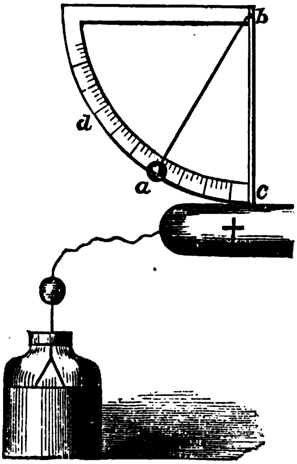


Fig. 104.

133. The gold-leaf electroscope may be used roughly as an electrometer to show the difference of potential between the leaves and surrounding bodies. The pith-ball electrometer, formerly called the quadrant electrometer, is a convenient form when we wish merely to judge when a body has received a certain quantity of electricity (fig. 104). It consists of a brass rod $c\ b$, which fits into the prime conductor; at

b is hinged a light wooden rod *b a*, which carries a pith ball *a*. The rod and ball pass over a quadrant scale *d*. If no jar be connected with the conductor, a very few turns of the handle of the machine will send the ball far away up towards *d*, and there it will stop, the conductor quickly attains its maximum potential; all electricity beyond this amount escapes into the air. But if the Leyden jar be attached, it takes a longer time for the high potential to be reached. The outer coating keeps the earth's potential, the inner goes on increasing in quantity, and *pari passu* in potential. But owing to the inductive condensation, a much larger quantity must enter the jar for the potential to be as high as before. This happens when the ball *a* stands as high as it did before. Beyond this, as before, no working of the machine will increase the charge.

134. The law connecting electrical attraction and repulsion, with the distance at which they take place, was established by use of the torsion electrometer. A thin wire *a* (fig. 105), fastened above to a nut *b*, which carries an index *c* working over a scale of degrees *d*; the nut and scale are supported on a glass tube *e*, which is fastened to a glass cover on the cylindrical glass vessel *g*; the wire *a* carries a horizontal rod of shell-lac *h*, at one end of which is a gilt pith ball *i*; the ball *i* rests against another gilt pith ball *k*, which is connected by a wire passing through the plate *f* to another ball *l*. Around the cylinder is a scale of degrees *m*, in the same plane as the plane of rotation of the stick of shell-lac. The whole is so arranged that when *i* and *k* are in contact, *i* is just opposite the zero of the lower scale, and the index of the upper

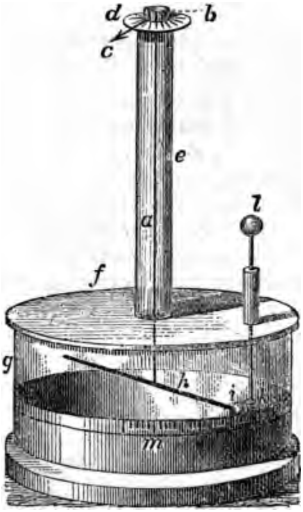


Fig. 105.

nut is also at zero on the upper scale. Let *l* receive a charge, this is immediately shared with *k* and *i*; they repel one another, and *i* is driven away and brought to rest by the torsion of the wire *a*. By the law of torsion, the angular disturbance of *i*, as measured on the scale *m*, is the exact measure of the force of torsion, and therefore of the force of repulsion. We may call the force of repulsion, therefore, simply α, if α be the angle of torsion. And if r be the radius of the circle along which *i* moves (fig. 106), the distance in a straight line between *i* and *k* is $2\ r$ sin. $\frac{\alpha}{2}$. Let now the nut *b* be turned in the opposite direction to that in which *i* moved until the direct distance between *i* and *k* is half what it was before, and let B be the angle now between *i* and *k*. Then $2\,r\,\text{sin.}\,\frac{\alpha}{2} = 4\,r\,\text{sin.}\,\frac{\beta}{2}$, or $\text{sin.}\,\frac{\alpha}{2} = 2\,\text{sin.}\,\frac{\beta}{2}$. In order to effect this, it is found necessary to turn *b* through an angle γ, such that $\gamma + \beta = 4\,\alpha$. In other words, to halve the direct distance, the torsion must be increased four-fold. And, universally, the repulsion varies inversely as the square of the distance. For small angular disturbances, the chord so nearly coincides with the arc, that the arc or angular displacement may be employed without sensible error in place of the straight line distance. That this is, indeed, the law of electrical attraction and repulsion, is proved by the circumstance that a body inside an electrified shell is not electrically disturbed, however it may be situated towards the circumference. If it be near one side, its nearness to the side is exactly counterbalanced, as far as electrical effect is concerned, by the larger amount of more distant surface on the other side, which tends to influence it in the opposite sense. The same is true with gravity. A heavy point will remain at rest anywhere within a hollow attracting shell. And this can happen nohow but by the existence of the law of attraction, varying inversely as the square of the distance.

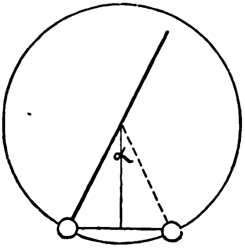


Fig. 106.

135. Another form of electrometer employs the directive magnetism of the earth, in place of torsion, to bring repulsion to rest. A ring of brass A (fig. 107) carries a knob of brass B above, and is supported below on the isolating support C. From the lower inside of the ring rises a metal point D, upon which turns a short bar magnet *n*, *s*. Fastened to this, and also in a horizontal plane, is a smooth gilt wooden rod E, F. When the needle has arranged itself in the magnetic meridian, the stand is turned round until the rod E, F touches the ring. On giving a charge to the knob B, the ring A and the bar E, F also share it, repulsion ensues, and the rod takes up a position when it is in equilibrium between the repulsive force, between the similarly electrified bodies and the directive magnetism of the earth. The latter increases to its maximum at 90°, when the needle is east and west. The former diminishes, not only as the distance of each end of the rod from the ring increases, but because repulsion ensues and increases in the opposite direction from the opposite side of the ring. The indications of this electrometer are also not independent of the ever-varying absolute magnetism of the earth.

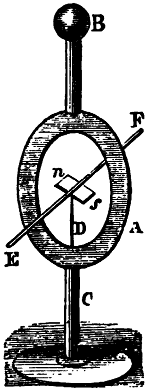


Fig. 107.

136. The Quadrant Electrometer, to which the name is now more generally given, is similar in principle to the above; but it has several advantages. It is seen in fig. 108 in its simplest form. It consists of four brass quadrants A, B, C, D, in a horizontal plane, forming a brass circular disc, with diametrical strips cut out. Each quadrant is connected below with the opposite one. Thus, A and C are connected, so are B and D. Two brass knobs, with wires E, F, are connected with two neighbouring quadrants, and these form the poles of the instrument. Above the centre of the quadrants, and above one of the diametrical divisions, is hung an aluminum sheet, with smooth edges G, of the form shown in the margin. G is hung by a very thin silver or platinum wire from the inside of a small Leyden jar H, which is supported by I, and whose inside is in connection with the knob K.

The adjusting supports, glass shade, and means for keeping the instrument dry, are not shown. If K receive a charge, say of + electricity from an electrophoros (Art. 45), the needle G shares it, and remains at rest as long as E and F are equipotential. If E be connected with the earth, so are D and B. Then if F receive a charge of + electricity, C and A share it, and there is repulsion between them and the needle, causing the latter to turn in the opposite direction to the hands of a watch when looked at from above. A little plane vertical mirror L is fastened to the torsion wire, and a beam of light is focussed upon it. The motion of the reflected image of this beam, on a distant scale, shows and multiplies the apparent motion of G. If F receive a – charge, the needle G moves in the opposite direction. Means are employed, which need not here be described, for keeping K and G uniformly charged. By this instrument the difference of potential between the earth and a body brought near or touching F can be measured, or if both E and F are isolated, the difference of potential of two bodies in contact with them can be measured.

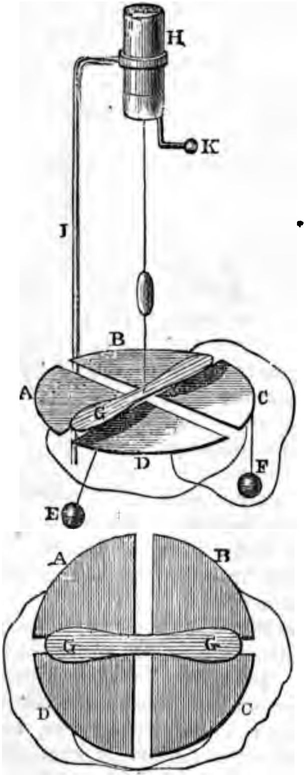


Fig. 109.

137. How high tension electricity is developed by contact of dissimilar conductors, will be considered in Book II., where chemical change will be considered as one of the sources of *low tension, or* galvanic electricity.

BOOK II.

VOLTAIC ELECTRICITY.

◆

CHAPTER I.

SOURCES OF VOLTAIC ELECTRICITY.

138. The terms Voltaic Electricity, Galvanism, Dynamic Electricity, Low Tension Electricity, Current Electricity, Contact Electricity, and Chemical Electricity, are used as names for the kind of electricity which has to be examined in this Book. The relation between this kind of electricity and that considered in Book I., does not find its counterpart by the comparison of any other two known physical forces; and although frictional and voltaic electricities are most intimately related to one another, they are scarcely more so than are light and heat, or even than heat at rest (in the sense of undergoing no change of place or quantity), and radiant heat. It is better until the common origin of the two is better understood, and hence their precise relation to one another established, to use some trivial name, such as voltaic electricity, rather than one which may only serve to perpetuate our present very imperfect knowledge. The reason why the other expressions have been used will abundantly appear in the sequel; for each expresses an important series of facts. Our first object will be to show that certain of the effects which we have seen in Book I. to be produced by frictional electricity, are also producible by this new kind of electricity.

139. **Preliminary Connection between Frictional and Voltaic Electricity.**—If a piece of ordinary impure zinc* be

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* Containing usually iron, arsenic, and sometimes cadmium.

plunged into a glass of dilute sulphuric acid, so that a portion of it is above the liquid, bubbles of hydrogen appear on the surface of the metal in the liquid: this portion gradually dissolves, and sulphate of zinc is formed. Perfectly pure zinc is not attacked by the acid. Pure copper is also not attacked by dilute sulphuric acid. A strip of zinc and a strip of copper may be partly immersed, side by side, in a glass of dilute sulphuric acid, and so remain for an indefinite time without being acted on. Let now their projecting ends be connected by a wire of any metal. Immediately the zinc begins to dissolve, and bubbles of hydrogen collect on and rise from the surface of the copper. This action ceases immediately the metallic external communication is interrupted and recommences as soon as it is re-established.

140. Let a wire (fig. 110) be fastened connecting the zinc, Zn, with one plate A of a condenser (Art. 67), and another wire connecting the copper, Cu, with the other plate B. Let both plates be isolated, and let A be connected with the electroscope C, and B with the electroscope D. Connect A and B metallically for a moment, and then disconnect them.

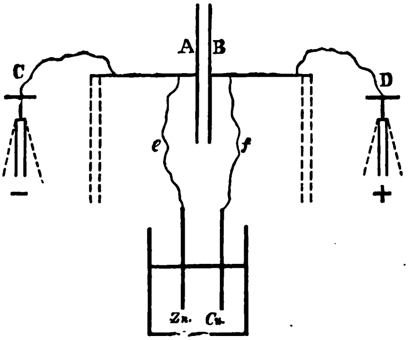

Fig. 110.

Next, disconnect the wires *e* and *f*, and remove the plates A and B from one another. The electroscope leaves D will diverge with +, those of A with − electricity.

Or, on touching the Cu with a proof-plane, sufficient +

electricity collects upon it to give motion to the needle of the tangent electrometer of Art. 136, Book I. Sufficient – collects on Zn to give to the proof-plane the power of turning the needle in the opposite direction.

141. Next (fig. 111), connect Zn and Cu by a wire, and stretch a portion of the wire horizontally north and south. Place a magnetic needle SN beneath the wire. The end N, which points to the north, will turn to the east, just as if Cu had been the prime conductor of an electrical machine, and Zn the – conductor on the earth. Compare Art. 108, Book I. Again (fig. 112, 1), place the connecting wire in any horizontal position, and lay a non-magnetic steel needle above and across it. The needle will become magnetised, fig. 112, and its end A will afterwards point to the north, just as in Art. 107, Book I., it was found that a discharge from a jar effected the magnetization of a needle lying on a piece of tin-foil through which the discharge passed. And precisely as in the latter case, when the + spark was sent in the opposite direction, the magnetic poles were reversed, so here (fig. 112, 2), if C be connected with Cu and D with Zn, then A B will be found to be so magnetised that A points to the south and B to the north. Clearly, therefore, the wire connecting the copper with the zinc is in some respects in the same predicament and condition as the wire connecting the + conductor of the electrical machine with the earth or with the – conductor. But the conditions of the wire in the two cases is far from identical. The wire conducting the prime conductor with the earth has to be wound round the magnetic needle a very great number of times (Art. 108), and the needle has to be rendered astatic in order that it may be swayed by frictional electricity. A single roughly hung needle is swung violently round by the zinc and copper connecting wire passing parallel to it above or below. Con-

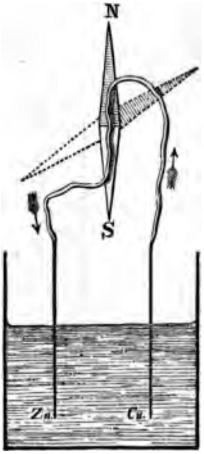

Fig. 111.

sequently, we might judge that the electricity of the zinc and copper-connecting wire were simply more powerful or greater in quantity than that of the conductor and earth-connecting wire. And this view would be supported by the fact that the copper-to-zinc wire is incomparably more powerful in magnetizing and demagnetizing a bar of steel laid across it than is the tin-foil of Art. 107, through which a series of sparks pass from a powerful Leyden battery. But while the spark from a frictional machine may be some feet in length, while the condensed spark of the Leyden battery may be several inches, and the lightning flash several miles long, the electricity of the copper-to-zinc wire is destroyed, that is, its magnetizing and demagnetizing power, when the ends of the wire are separated by even so small an interval as the thousandth part of an inch.

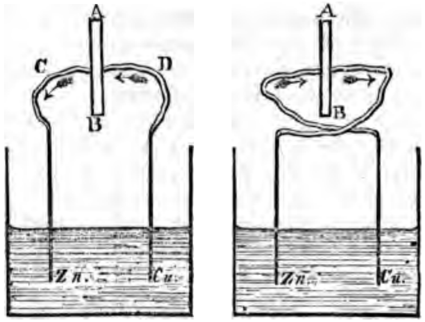

Fig. 112.

That which can be interrupted or destroyed by introducing a break in an otherwise continuous system, we are almost involuntarily led to consider as a current in that system.

142. And so it is supposed that there exists a current of this new kind of electricity, voltaic electricity, through the wire, which is a conduit or conductor (fig. 113); and further, that as far as the direction of the current is concerned, the projecting copper of the voltaic couple is in the analogous state to the prime conductor of the frictional machine. Let *now (fig. 114)* the horizontal portion, *a b*, of the copper-to-zinc wire be arranged north and south, and let the needle be placed beneath it, the current passing from *b* to *a* will turn the north-pointing end of the needle to the W., or in the direction of the hands of a watch. Place the needle beneath the cell, and it will turn in the opposite direction, proving that there the current passes above the needle in the opposite direction, or from S. to N. The current passes in a complete circuit, through the liquid, from the zinc to the copper, through the connecting wire from the copper to the zinc.

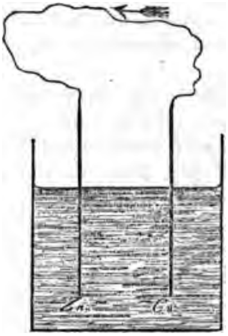

Fig. 113.

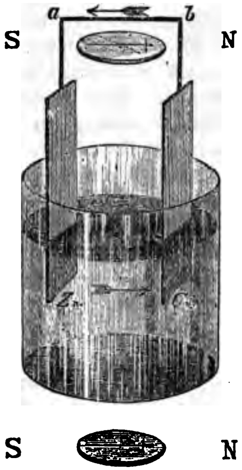

Fig. 114.

This we may call the + current, since it produces identical effects with the frictional current from the + conductor. As in the case of frictional electricity, we imagined – electricity to be always cogenerate with +, and to pass always in the opposite direction to the +; so here we may, if we please, suppose that a – current passes through the liquid from the Cu to Zn, and through the wire from the Zn to the Cu. There is no more reason why the one direction should be called in preference the direction of the + current, than there is why glass should be considered + ly electrified when rubbed with amalgamed silk. But if the prime conductor be called +, then the copper must be considered the + pole of the voltaic cell out of the liquid.

143. Origin of Current.—Two things are essential for the establishment of a voltaic current—(1.) There must be a complete circuit of conducting matter. (2.) Some molecular disturbance must take place at some portion of the circuit where there is an interruption in the homogeneousness of the circuit. Of course the condition (2) implies the want of homogeneousness throughout the circuit. Given therefore a complete conducting circuit, a dissimilarity between some two of its contiguous parts, and a molecular disturbance at that point of discontinuity: then a current will traverse the circuit. The molecular disturbance may be caused by external means, as by the application of heat; or it may be brought about in a spontaneous manner, as when the zinc and sulphuric acid acted chemically upon one another.

144. It is clear that in the elementary zinc-copper sulphuric acid cell, since metallic or other conductive contact outside the cell is essential to the formation of the current, we may look upon P (fig. 115), as the origin of the current in the simplest case of extra liquid contact, and conceive the current to be started by the extra liquid contact of the dissimilar metals. The force which sets the current moving around a closed circuit is called the electro-motive force, and its amount is, of course, independent of the view which is taken of the origin of the force.

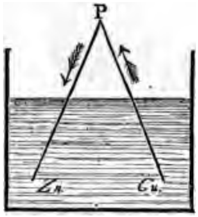

Fig. 115.

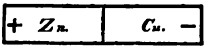

Fig. 116.

145. What is called the contact theory of the origin of the electro-motive force and current assumes that when two dissimilar metals are in contact, there is at the surface of contact an analysis of the common electricity of sufficient strength and constancy to maintain the two touching metals in opposite electrical states. The zinc *becoming* + and the copper −. It is an undoubted fact that for some time after the contact is made such polarity is observed, and may be detected by making the two semicircular, and extending over the line of junction a + ly charged needle N, fig. 117. The needle N, if delicately suspended, will turn towards the copper, showing that the latter is –. A – charged needle turns in the opposite direction.

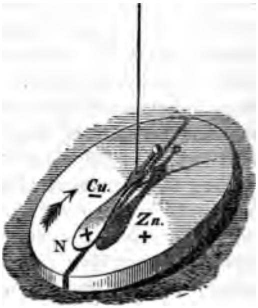

Fig. 117.

146. Again, if (fig. 118) we place a copper-condensing plate P, varnished on its under surface on the copper plate Q (of the electroscope), varnished on its upper surface, we have the means of accumulating electricity from such sources. A rod of copper Cu is soldered to a rod of zinc Zn. The latter is held in the hand, and the under (unvarnished) surface of the electroscope is touched with the copper, while the finger of the other hand touches the upper (unvarnished) plate of the condenser. The finger and rod are removed, and on lifting the condensing plate by the isolating handle H, the leaves of the electroscope diverge with – electricity. Positive electricity accumulates therefore on the upper and – on the lower plate. If the copper end of the compound rod be held in the hand, while the lower side of the electroscope plate is touched with the zinc, it is not found that the electroscope charges itself with +. Nor is a – charge collected if the zinc end be protected from the hand

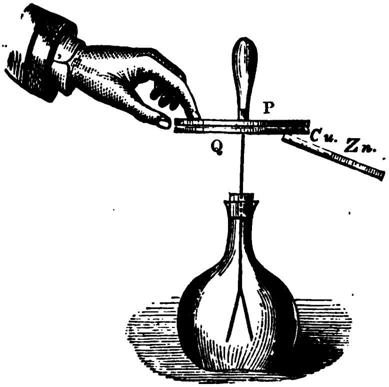

Fig. 118.

by flannel, although the zinc may be connected with the earth, or the upper plate by a wire. Hence it is usually admitted, at least in England, that the development of electricity in this case is due to the chemical action between the saline moisture of the hand and the zinc. Those who look upon the contact of the dissimilar metals as the seat of the electrical separation, while admitting the chemical action between the zinc and the hand, regard the moisture of the hand simply as a conductor which undergoes decomposition; and view the non-existence of the accumulation, when metallic connection is made between the zinc and the condenser, as due to the equal and opposite current set up between the connection and the zinc.

147. That contact between a single metal and a liquid is sufficient to cause electrical excitement, is seen in the experiment shown in fig. 119. The electroscope is furnished with a zinc plate Zn, to which is fastened a zinc strip Zn. Upon Zn is placed a very thin dry varnished glass plate G, and upon this again a little acidulated water A W. On bringing the free end of Zn into the water, + electricity accumulates in the water, and – in the electroscope, as is seen on lifting the glass G, whereupon the leaves diverge with – electricity. If the experiment be tried when copper is substituted throughout for zinc, a – charge also collects on the electroscope, but not of so strong a nature as when zinc is used.

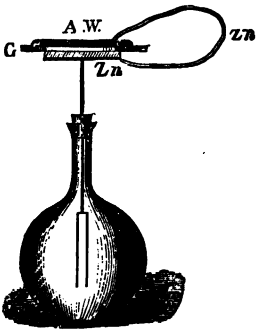

Fig. 119.

148. The experiment of Art. 145 seems then to show that electrical excitement can be produced by contact alone of dissimilar metals. The experiment of Art. 147 seems to show that a single metal and a single liquid in contact with it, and having an action upon it, produce chemical excitement. Advocates of the chemical origin of electricity argue that the zinc and copper semicircular discs of Art. 145 are acted upon by the oxygen and moisture of the air in such a way that the zinc is gradually though imperceptably corroded, and that we have, in fact, a feeble cell. Advocates of the contact theory argue that, in Art. 147, we do not deal with a simple sheet of metal, but with a metal covered with a film of oxygen. Again, it is found that if two isolated discs, one of copper and the other of zinc, are pressed gently together and then separated, and brought into contact respectively with the upper and lower condensing plates of a gold-leaf electrometre, the leaves of the latter become slightly charged. The charge is increased on repeating the pressure and contact. Here, however, it may be argued that we are not dealing with simple metallic surfaces, but with surfaces covered with oxygen; or that perhaps an inappreciable but still definite amount of mechanical work is done in the separation of the plates. That contact between dissimilar metals gives rise to only feeble currents, unless the contact be assisted by some great molecular disturbance, such as heat or chemical change in some part of the circuit where there is discontinuity of kind, will be abundantly illustrated.

149. In the simple cell, Art. 139, we have seen how the zinc is not attacked by the dilute sulphuric acid until the neighbouring copper is connected with the zinc out of the liquid. If now (fig. 120) the two metals touch one another beneath the surface of the liquid, the zinc is attacked as before, and a + current circulates from the zinc through the liquid to the copper, and from the copper through the metallic junction to the zinc. It is to this promotion of chemical action by contact, either outside or inside a liquid, of a less easily attacked metal by the establishment of an electric current that the rusting of iron palings is due, where they are fastened into stone by leaden stopping. A like action is set up when zinc or iron rivets are used in a copper-bottomed vessel. Further, Art. 139, we have seen that when the circuit is complete, hydrogen is evolved in the copper surface of the cell. Hydrogen when freshly liberated has, as is well known, an exceedingly power-

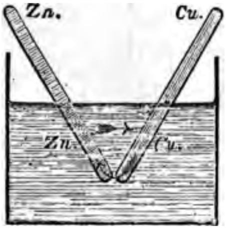

Fig. 120.

ful reducing action. Use is made of these circumstances to protect the copper sheathing of ships. Lumps of zinc are fastened to parts of the sheathing. Between the zinc and the copper a galvanic action ensues when the two are in contact with the salt water; the zinc rapidly corrodes and dissolves in the sea, while the evolution of hydrogen on the copper surface deoxidizes any oxidized portion.

150. Crown of Cups: Voltaic Piles, Dry Piles.—After the nature of the zinc-copper connecting wire of a single cell had been examined, attempts were made to increase the effect and exalt the condition of the wire by the combination of more than one cell, in a manner similar to that in which the intensity of the electric discharge is increased, Book I., Art. 82, by the combination of several jars to form a battery. The force which sets the electricity moving, when the Cu and Zn of a single cell are joined, is called the electro-motive force, and the current strength depends upon this electro-motive force, modified by the resistance. (The current strength is equal to the electro-motive force divided by the resistance).

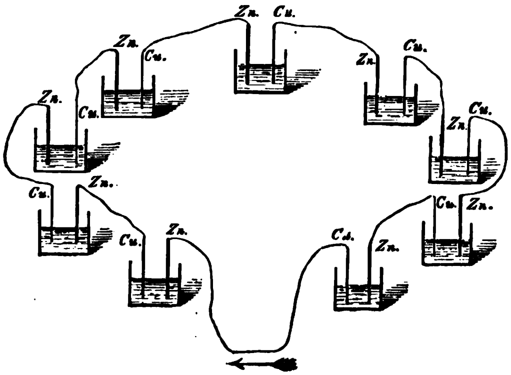

Fig. 121.

If *n* cups (fig. 121) are joined together in such a manner that the Zn of one is joined to the Cu of the second, the Zn of the second to the Cu of the third, and so on, the Zn of the last or *n*th being joined to the Cu of the first; there will be *n* times the electro-motive force. Such an arrangement is called the crown of cups; it reminds one of the cascade arrangement of the Leyden jars, supposing each jar to have originally the same charge or difference of potential. The electro-motive forces of all the cups tend in the same direction, and, where the current is rendered possible by connecting them as above, a stronger current passes. The crown of cups is one of the simplest forms of the galvanic battery. Such a battery consists of separate cells, or, as they are sometimes called, *elements.* Each element consists of a *pair;* that is, in this case, pieces of zinc and copper. Each pair has two poles, the copper or + and the zinc –. The extremities of wires connected with these are also called the poles. If the circuit of a battery be broken, that end of the broken wire which is in connection with the copper of one extreme cell of the battery is the + pole; the end of the wire in connection with the zinc of the cell at the other extreme end is the – pole.

151. The arrangement of fig. 122 shows the voltaic pile, which is perfectly similar in principle to the crown of cups. A series of equal sized discs of zinc and copper (fig. 122) is arranged in pairs, the zinc being the uppermost in each pair. Upon the top of the first or lowest pair, is placed a somewhat larger circle of flannel *f*, steeped in brine or any dilute acid: preferably such as does not attack copper when the two are alone. The second pair is placed on the flannel, a second piece of flannel is placed on this, and so on, the zinc of each pair being always kept above the corresponding copper with which it is in direct contact. There is accordingly a disc of copper above and a disc of zinc below. These, or wires connected with these, are the poles of the pile, the copper and its wire being the +, the zinc and its wire the –. When the wires are joined, a feeble spark is seen between them; when they are connected by the brine-

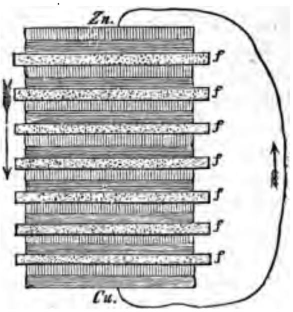

Fig. 122.

moistened fingers, a feeble shock is felt. After connection, when examined by the magnetic needle (Art. 142), the + current is found to pass from the copper to the zinc. On examining the pile itself by the needle, the + current is found to pass from above downwards (Art. 141).

152. Whatever be the nature of the metals and liquid, there must be consumption of material in such a pile; one or other of the metals must be attacked by the liquid. The attempts which have been made to protract this action, and consequently to dilute it with time or enfeeble it, have resulted in the construction of the dry piles. The two chief kinds of these which have been constructed, are the tin and copper, and the tin and peroxide of manganese piles. To construct the former, some sheets of paper are covered with paste on both sides: on the one side is stuck tin-leaf, on the other copper-leaf. When the whole is dry, circular discs are punched out of it, which are placed in a glass tube, varnished in the inside in such a way that all the copper faces of the discs are either upward or downwards, the tin faces being all downwards or upwards. The tube has two brass caps at its ends, the lower one being (say) in contact with the zinc face of the lowest disc, the upper one in contact with the copper face of the upmost disc. By means of the upper cap, the discs are pressed firmly together. The tin pole of this pile is – the copper as before +.

If silver-leaf be pasted on one side of a sheet of paper, and the other be covered with finely-powdered peroxide of manganese rubbed into the paper, similar discs may be stamped out and arranged as before, with their tin faces upwards, in a varnished glass tube provided with caps. The silver end is +. Such dry piles exhibit, after some time, considerable development of electricity, and they may last for years in action. The + and – electricities at their poles accumulate and condense to such a degree, that they at once deflect the leaves of the galvanometer, and may even charge a jar of small size. But the resistance inside the pile is so great, that when the poles are joined but a very feeble current can traverse the circuit, and almost absolutely no magnetic or other effect can be shown. The small amount of low tension *or current electricity* generated, by the slow chemical reaction in the pile, is condensed into high tension or frictional electricity by the inductive action on one another of the numerous and almost isolated opposed electrogens. Of such conversion we shall have frequent examples in the sequel. The polarity of such a pile is sufficiently great to keep in oscillation a metal rod *a b* (fig. 123), which is delicately hung by cocoon silk in the same horizontal plane as the pile, and in such a way that the ends of the rod nearly touch the poles. The action requires no explanation. It continues for years, but inevitably ceases at last.

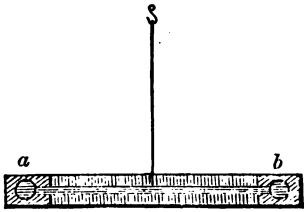

Fig. 123.

153. The dry pile electroscope is an adaptation of the same principle. It is clear that a single isolated gold leaf will move towards one or other of the poles of the dry pile, according as it is + ly or − ly electrified. Thus, in fig. 124, AB is the pile, *a* and *b* the corresponding poles which pass through the wooden support C into the inside of the electroscope jar D. Midway between *a* and *b* is suspended the single gold leaf E in the usual way. On approaching an electrified body to the knob K, the leaf sways to *a* or *b*, according as the body is − ly or + ly electrified, if A be the copper and B the tin end of the dry pile.

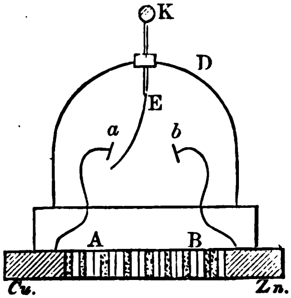

Fig. 124.

154. Relative Polarity of Metals or Series of Electric Tension.—Whatever be the nature of the wire connecting zinc and copper, the (+) current passes from the Cu through the wire to the Zn when the two are plunged in dilute sulphuric acid; also when the current is broken, + electricity of some tension collects on the Cu and − on the Zn. In the liquid, therefore, the Zn is + compared with the Cu, but it is the – metal which forms the + pole. On comparing metals with one another in this way, and determining their relative polarities or signs, we obtain what is called an electro-chemical series. It must be borne in mind that such a series is strictly relative, and that a metal which is + to a second may be – to a third. Also, that the relative polarity or sign depends in a great measure upon the nature of the liquid in contact with both. It is invariably found that when a current is found pass into the liquid from A to B, it is the metal A which is found to be mainly attacked—generally it alone is attacked. The very fact that hydrogen is evolved on the – metal, insures the latter remaining unattacked. To this rule there is no exception. It is also a general, but not universal, rule, that if examined separately in a liquid, A is attacked and B not at all, or less readily, then the current will pass in the liquid from A to B. In the following tables, the metals are arranged in electro-chemical order: those at the top being + to those below, when the two form a pair in the liquid at the top of the list.

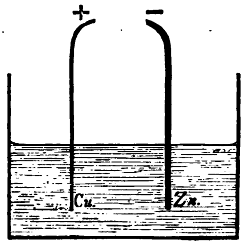

Fig. 125.

Caustic Potash.	Hydrochloric Acid.	Sulphide of Potassium.	
+	+	+ or	+
Zinc	Zinc	Cadmium	Zinc
Tin	Cadmium	Zinc	Copper
Cadmium	Tin	Copper	Cadmium
Antimony	Lead	Tin	Tin
Bismuth	Iron	Antimony	Silver
Iron	Copper	Silver	Antimony
Copper	Bismuth	Lead	Lead
Nickel	Nickel	Bismuth	Bismuth
Silver	Silver	Nickel	Nickel
	Antimony	Iron	Iron
	Gold		
	Platinum		
	Rhodium		
	Graphite		

It will be seen that the same order is not preserved in each list. Slightly different results have been obtained by different experimenters, so that too much importance must *not be attached to* the results. Very slight impurities in the metals, and in the connecting liquid, make very serious alterations in the relative polarities of two metals.

In the third column, the results of two series of observations are given in order to give an idea of the uncertainty which still prevails. The texture of the metallic surface also influences the polarity. If a sheet of smooth and a sheet of roughened zinc are employed in dilute sulphuric acid, as a pair, the rough zinc is found to be +. On heating one of the two plates of a pair of identically the same metal, the + current passes for a moment from the hot to the cold, until the two attain the same temperature.

Plunged into strong nitric acid, iron is not attacked, and is, moreover, rendered less attackable by other acids. Thus rendered passive, it may serve as a – metal, and so form the + pole, when paired with some of the metals beneath it in the above tables, or with iron itself in its normal state. With regard to each of the above series the important rule has been established, that if a current of strength E_1 is set up from A to B, when those metals form a pair, and a current of strength E_2 from B to C, when the latter form a pair, then, on forming a pair of A and C, a current will pass from A to C, with a force $E_3 = E_1 + E_2$. And, in general terms, the current between A and N is in strength the algebraical sum of the currents of any consecutive order, when A is the first and N the last term. Thus denoting the metals by their chemical symbols, and supposing the same pieces of metal and the same liquid H.Cl to be used, we have, from column three—

Zn current Ni = Zn curnt. Pb + Pb curnt. Fe – curnt. Sn + Sn curnt. Ni.

155. Such a series was first obtained by employing the method of observation described in Art. 146. Compound bars of the various metals, similar to the compound Zn and Cu bar, being held in the hand by one metal, the other is brought in contact with the condenser of the electroscope, while the cap is touched (or the reverse), as described in Art. 146.

156. The following series is thus obtained :—

+
Zinc
Tin
Iron
Lead
Copper
Silver
Gold
Platinum
Carbon (graphite or coke).
–

CHAPTER II.

GALVANIC BATTERIES.

157. The Failure and Exhaustion of Currents.—The crown of cups and the voltaic pile are the primitive forms of a battery. Such batteries, after a few minutes' work, that is, after the completion of the circuit, are found to quickly fall in power. On examination into the cause of this failure, it is found to depend mainly on three circumstances: The metal which is attacked dissolves in and neutralizes the acid; and since we may look upon the attack on the metal as essential to, if not the prime cause of the current, when that attack slackens the current falls in strength. Secondly, as mentioned in Art. 139, hydrogen is evolved on the – metal (copper). Although only visible when it has collected in bubbles of some size, we must admit that when evolved it covers the copper uniformly, however thinly, and owing to the almost complete impenetrability of a gas towards low tension electricity, the copper is thereby protected from contact with the liquid, and the circuit is interrupted, soon after its establishment. Thirdly, the hydrogen thus evolved on the surface of the copper, does not merely act as a mechanical obstruction, but, spread on the copper plate, acts like a strongly electro-positive metal even more + than the zinc, and so seeks to force back the current from the copper to the zinc in opposition to the proper direction of the zinc and copper pair.

The existence of this tendency may be proved as follows:—Let a zinc and copper pair, placed in a cell of dilute sulphuric acid, be connected together by a wire running north and south, from the copper to the zinc, beneath a magnetic needle (fig. 126). The needle will turn so that its north end moves *to the east. Let this* action continue for some time. Then remove the liquid and replace the zinc by a sheet of copper; fill up the vessel again with acid, and the needle will be seen to turn in the opposite direction (fig. 127), proving that the current passes beneath the needle in the opposite direction, and, therefore, passes in the opposite direction through the liquid, namely, from the hydrogenized copper to the normal copper. Such an action must of course be short-lived, for the very passage of the current oxidizes the hydrogen, as it previously oxidized the zinc, and develops hydrogen on the fresh – copper, which straightway sets itself to oppose the current. But though thus only momentary when withdrawn, the opposition is continual and accumulative in the original cell, until a condition is established, in which a feeble and irregular current is established from Zn to Cu. The electromotive force of gases freshly generated will be more fully described in the sequel. We may here recall the circumstance that both hydrogen and oxygen have very great reducing and oxidizing powers respectively when they are newly liberated, or, as is sometimes improperly said, when they are in the nascent state.

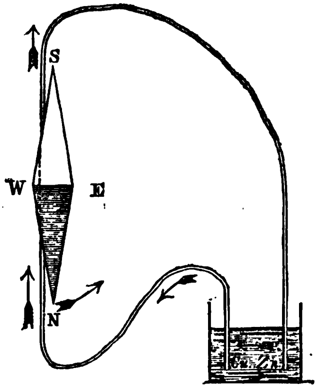

Fig. 126.

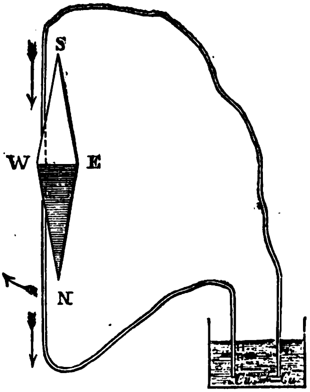

Fig. 127.

158. Accordingly, one of the chief objects to be aimed at, in constructing a battery, is to get rid of the reaction of the hydrogen in the opposite direction to the current proper.

For effecting this there are two ways. By one the liberated hydrogen is oxidized by oxygen belonging to the oxide of a metal, the metal itself being set free and deposited on the surface, where otherwise the hydrogen would have been evolved; by the other the liberated hydrogen is oxidized by the oxygen belonging to some non-metallic oxide, such as nitric acid, or by some metallic oxide such as chromic acid, whose lower oxide is soluble in acids.

159. To understand how this is effected, let us return for a moment to the consideration of the single cell. Let the metals be zinc and copper, and the connecting liquid dilute hydrochloric acid. We find that chloride of zinc is formed at the zinc, and hydrogen liberated at the copper. How does it take place that the hydrogen is not evolved at the zinc, for it is there that the zinc deprives it of its chlorine? It is not easy to conceive the destitute hydrogen penetrating through the mass, and appearing personally at the copper; but it is possible to conceive the hydrogen, which is deprived of its chlorine by the superior attraction of the zinc, combining with the chlorine belonging to a neighbouring mass of hydrochloric acid. Hydrogen would thus again be liberated, which, in its turn, would combine with neighbouring chlorine, and so on. The hydrogen would never appear free until the series of decomposition reached as far as the copper, where meeting with no more chlorine ahead of it in the direction of the current, and having small affinity for copper, it escapes. The arrangement of the hydrochloric acid is shown in fig. 128; the upper brackets indicate the connection between the hydrogen and chlorine before the current passes, the lower brackets show the condition when the current passes. There is no molecular work done when a quantity of hydrogen forsakes its chlorine to combine with the same quantity of fresh chlorine. We may compare the ease with which such a transfer of combination is effected to the ease with which a chain hanging *over a pulley* is moved. When the two sides are equal, each

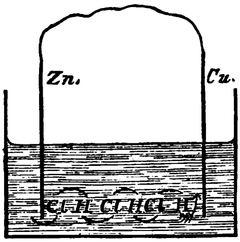

Fig. 128.

link on one side may be conceived as keeping in equilibrium the opposite link on the other side. A slight force pulling one side down will bring each link opposite to a different one.

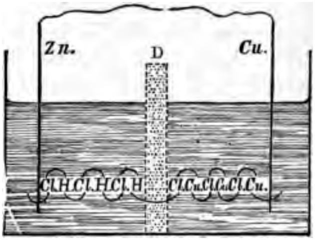

Fig. 129.

160. Let the cell of fig. 129 be divided now into two parts by a division of porous earthenware D, fig. 129. Let the zinc be, as before, surrounded by dilute hydrochloric acid, and let the copper be surrounded by a solution of chloride of copper* instead of the chloride of hydrogen (hydrochloric acid), of Art. 159. The two liquids soak into the porous wall D and touch one another, but are prevented from mingling freely with one another. The chlorine, as before, forsakes its proper hydrogen to unite with the zinc, the forsaken hydrogen combines with its neighbour's chlorine, and so on as before, till the change reaches the porous cell. Here the forsaken hydrogen unites with chlorine, of the chloride of copper, and the forsaken copper unites with its neighbour's chlorine, and so on till the copper pole is reached; the last copper of the chloride having no chlorine to lay hold of is deposited in the metallic state upon the copper pole increasing its thickness. By this device hydrogen is prevented from appearing at the copper pole, and so it is prevented from isolating the pole by a gaseous film, and from reacting back (Art. 157), so as to oppose the fundamental current. The hydrogen is replaced by copper. The deposition of copper from solution on to the copper pole makes, of course, the copper solution become gradually weaker. And the hydrochloric acid also loses strength by being gradually converted into chloride of zinc. The latter of these sources of failure is diminished by employing a large mass of acid liquid around the zinc; the former is obviated by keeping some solid copper salt in the solution (saturated) of copper which surrounds the copper pole.

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* At present we are not concerned with the relative quantities of the elements present. The symbols in the figures represent the elements, not their quantities. The chemical changes in the cell, and those affected by the current, will be considered in Chap. III.

The arrangement actually employed in such a constant cell, or battery of cells, is identical in principle with the above, but is somewhat modified as follows:—The arrangement to be described is called Daniell's cell or battery (fig. 130). A cylindrical copper vessel A is provided with a perforated shelf trough, running round its upper inner edge.

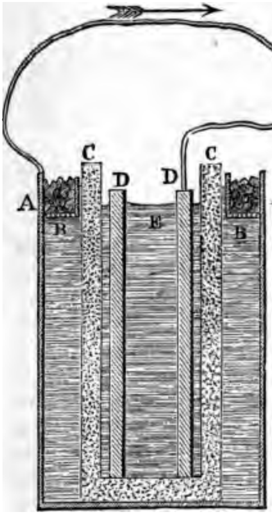

Fig. 130.

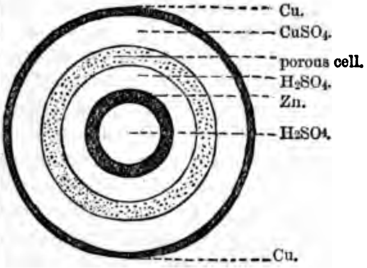

Fig. 131.

This trough is filled with crystals of sulphate of copper ($CuSO_4$). Next towards the inside is a cylindrical cell C C of unglazed and porous earthenware. In the middle is a hollow zinc cylinder D D. The space between A and C is filled with a saturated solution of sulphate of copper ($CuSO_4$), which reaches up far enough to be in contact through the perforated shelf, with the crystals of the same salt. The porous cell C C is filled with dilute sulphuric acid (about 1 of oil of vitrol to 12 of water). On joining A and D a *current passes* from A to D. The series of changes is precisely similar to that described in Art. 160. At the surface of D occurs the formation of sulphate of zinc ($ZnSO_4$).

$$Zn + H_2\,SO_4 = Zn\,SO_4 + 2H.$$

The disengaged hydrogen reacts upon its next neighbouring sulphuric acid combining with its SO_4, and liberating its H_2, and so on till the porous cell is reached, and sulphate of copper $CuSO_4$ encountered. Then the Cu engages in the same work until the copper surface A is encountered, and upon this the copper is deposited. The whole resulting change may be represented by the equation

$$Zn + SO_4\,H_2 + SO_4\,Cu = Zn\,SO_4 + H_2\,SO_4 + Cu, \qquad (1)$$

or, if we indicate a few of the intermediate recompositions,

$$\left.\begin{array}{l} Zn + SO_4H_2 + SO_4H_2 + SO_4H_2 + .. + SO_4\,Cu + SO_4Cu + .. + SO_4Cu \\ = ZnSO_4 + H_2SO_4 + H_2SO_4 + .. + H_2SO_4 + CuSO_4 + .. + CuSO_4 + Cu \end{array}\right\} (2)$$

161. It is clear that if the above expressed the whole truth, sulphuric acid would be formed where the two liquids meet, that is, in the pores of the porous cell, and we might expect free sulphuric acid to appear by diffusion in the neighbourhood of the copper. This is not the case. Further, if the action at the zinc plate were alone regarded, we might expect the battery to fail as soon as the free sulphuric acid in the zinc cell were converted into sulphate of zinc. Or, indeed, that if we used sulphate of zinc instead of sulphuric acid in the zinc cell the action would cease, the zinc ceasing to be corroded. This is not the case. The battery acts not, it is true, with so much intensity, but with far greater constancy if sulphate of zinc be substituted for sulphuric acid around the zinc. The action in this case must not be regarded as based upon the evolution of hydrogen by the zinc from the acid, and the reduction of the copper from its sulphate by the "nascent" hydrogen, but as depending upon the preference affinity of Zn over Cu to SO_4, or (since SO_4 is not known in the free state) more correctly, the tendency to the change expressed in the equation,

$$Zn + Cu\,SO_4 = Zn\,SO_4 + Cu,$$

which occurs when metallic zinc is plunged into sulphate of copper. In the battery cell it is true that the zinc is not in contact with the sulphate of copper. But the tendency to form $ZnSO_4$ at one end of the series of molecules is in direct communication with the tendency to remain $CuSO_4$ at the other, by a series of molecules which do not require any force expenditure to convey the balance of affinity. When the copper and zinc plates are connected, we may look upon the whole system of change as consisting of a transference of hydrogen, or its equivalent copper in the direction from the zinc to the copper. A transference of SO_4 from the copper cell towards the zinc with which it finally combines, forming sulphate of zinc. The solid sulphate of copper in crystals, which dissolve, supplies both the copper which is deposited on the copper plate, and the SO_4 which combines with the zinc. The zinc cell becomes gradually saturated with sulphate of zinc, which finally accumulates in such quantity as to crystallise out, and impede the action of the battery. We may look upon the tendency of the hydrogen or metal towards the copper as being translated there into an electric current (+) which ascends the copper, traverses the connecting wire, enters the zinc to again pass through the liquid. We may, if we please, consider a $-$ current passing in the opposite direction.

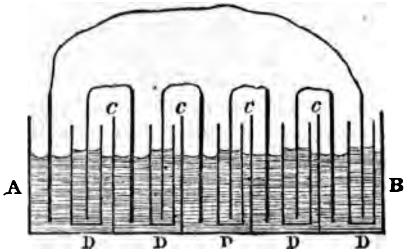

Fig. 132.

162. A compact form of Daniell's battery, such as is used in telegraphy, is shown in (fig. 132), in section. AB is a long wooden rectangular box divided into cells by square pieces *c,c,c,c,c*. The whole is thoroughly lined with marine glue. D,D,D,D,D, are porous cells. In the porous cells are *sheets of copper* and saturated solution of sulphate of copper.

Each copper is connected with a sheet of zinc hanging in the next cell of about twice its own size. The zinc is surrounded with a solution of sulphate of zinc of about half saturation.

163. Amalgamation of the Zinc Plates.—For uniformity of working, and for obtaining the maximum effect, it is essential that all parts of the zinc should be acted on equally by the acid or salt. Ordinary commercial zinc, besides the impurities mentioned in Art. 139, has, in the process of cooling, become unequally annealed, different parts of it are unequally hard, and are attacked with different facilities by the same acid. Pure zinc carefully annealed is not attacked at ordinary temperatures by pure sulphuric acid. Two pieces of zinc, one of which is more easily attacked than the other, will, when in contact with an acid and with one another, form a couple, the more easily attacked being + and and the less easily −, just like a piece of zinc and copper respectively. In fig. 133, E represents an easily, and D a difficultly attackable piece of zinc forming one piece. The arrows represent the direction of the current. A coasting trade. Such a heterogeneous piece of zinc when used as an element in a cell fritters away some of its general electro-motive power by establishing local currents. It seems that the chief cause of this inequality of action is due to difference of hardness rather than metallic impurities, for if the surface of the zinc be moistened with sulphuric or hydrochloric acid and mercury smeared over its surface until the zinc is uniformly amalgamated, such local currents are completely arrested. The metallic impurities cannot certainly be removed in the process of amalgamation. But inequality in hardness, due to irregular cooling, can easily be removed; for as the mercury penetrates, the mass softens and molecular strains are relieved, and uniformity results. This is so complete that amalgamated plates may be left in contact with dilute sulphuric acid for any length of time without dissolving, a condition almost indispensible when, as in the telegraph system, batteries are in repeated but intermittent use.

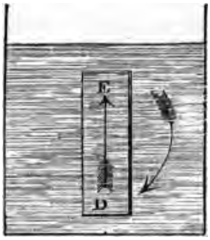

Fig. 133.

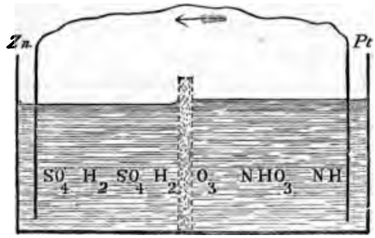

Fig. 134.

164. Platino-zinc, or Grove's Constant Battery.—The principle of this battery is to eliminate the hydrogen, not as in Daniell's by its replacement by copper, but by oxidizing it to water. For this purpose nitric acid is employed in contact with the – metal, which accordingly cannot be copper as in Daniell's cell. The – metal is a sheet of platinum (Pt., fig. 134), this is surrounded by nitric acid of the greatest strength. The zinc is, as before, surrounded by dilute sulphuric acid (1 : 12), and the two acids are separated by the porous wall A. We may start as before from the formation of sulphate of zinc at the zinc surface and trace the successively liberated hydrogen till it meets the nitric acid in the porous diaphragm. The hydrogen is oxidized to water by the nitric acid, reducing that body to peroxide of nitrogen (NO_2), or to nitric oxide (NO), according to one or other of the equations—

$$H_2+2HNO_3=2H_2O+2NO_2$$
$$\text{or, } 3H_2+2HNO_3=4H_2O+2NO.$$

It is not properly made out which of these equations more accurately expresses the re-composition which actually occurs. Red fumes of NO_2 arise from the platinum cell when such a platino-zinc cell or battery is in action; but whether the NO_2 is a direct product of the action, or the result of oxidation in the air of NO, is not ascertained; nor is it known whether other nitrogen oxides accompany the action. The fumes of NO_2 render the working of this battery in a confined space inconvenient. The neighbourhood of the battery must be well ventilated. The form which is usually given to the Platino-zinc, or Grove's Battery, is as follows (figs. 135, 136). In a glazed earthenware or ebonite rectangular cell A, is placed a thick sheet of amalgamated zinc B, bent so as to form a U-shaped part in the cell, and a projecting part out of the cell, for the purpose of attaching screws to bind the zinc of one cell to the platinum of the next. Inside the bend of the zinc is a narrow unglazed porous earthenware cell C, as wide as the zinc. In the porous cell C is a sheet of platinum foil D, as broad as possible. The strongest nitric acid is poured into the cell C and the space between the two cells, that is, the space surrounding the zinc is filled with dilute sulphuric acid (1 : 12). The cells may be joined together as is represented in fig. 137, by means of *screw clamps* embracing the zinc of one cell and the platinum of the other.

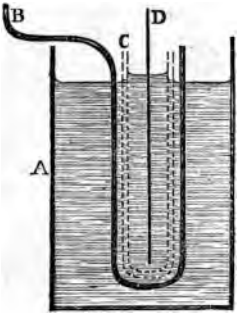

Fig. 135.

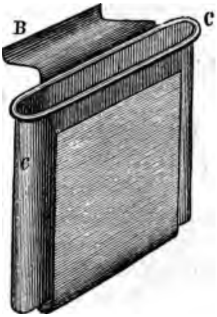

Fig. 136.

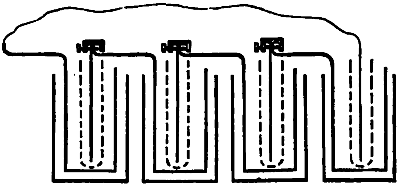

Fig. 137.

165. Carbo-zinc, or Bunsen's Cell or Battery.—This is a modification of Grove's battery. The platinum is replaced by carbon. The carbon used is sometimes the dense coke which forms the upper crust in gas retorts; sometimes it is specially prepared by heating bituminous coal in powder in moulds having the necessary form, surrounded by powdered charcoal in crucibles. When the latter plan is adopted three or four bakings of the carbons are necessary, the carbon being on each removal from the fire soaked in syrup. On

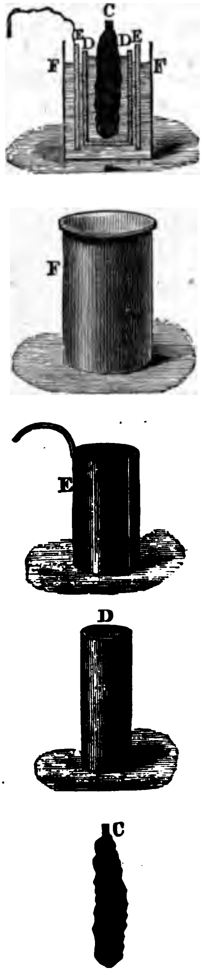

Fig. 138.

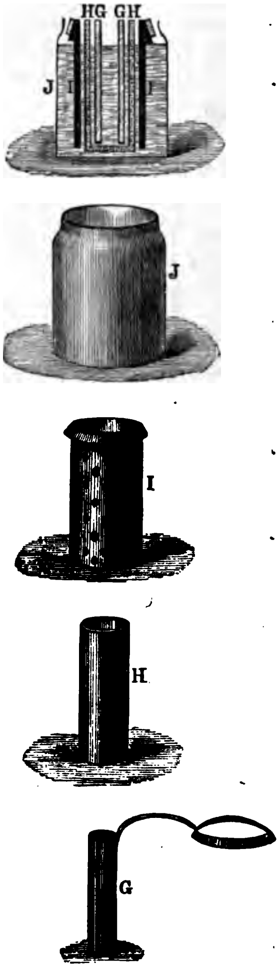

Fig. 139.

reheating, the syrup is decomposed, and the carbon deposited in the pores of the mass binds it together, so that at last a very coherent mass is obtained. If gas coke is used, it is generally in the form of a thick rod (C, fig. 138). This is placed in a porous earthenware cell D. Around D is a thick cylindrical tube E of amalgamated zinc, having a metal band to connect it with the carbon of the neighbouring cell. The whole is placed in a glass or ebonite or gutta-percha vessel F. Fuming nitric acid is placed in D, in contact with the coke. Dilute sulphuric acid (1 : 12) is between the cells in contact with the zinc. The arrangement is seen to be exactly analogous to the zinc-platinum cell.:

When moulded carbon is used, the form is generally that of fig. 139. A split cylinder of thick amalgamated zinc C, carrying a copper band ring (for attachment to the coke of a neighbouring cell) is placed in the porous earthenware cell H. Around H is placed the cylinder of carbon I, which is perforated to allow the circulation of acid, and which has a slightly conical top for the reception of the ring connected with the coke of the neighbouring cell. The whole is placed in the acid-proof cell J. In this form of the carbo-zinc cell or battery the nitric acid is between the cells, and, therefore, in contact with the carbon. Sulphuric acid is in contact with the zinc in the inner cell H. The top of the coke cylinder I is soaked in wax or paraffine to prevent the nitric acid from rising by capillarity and corroding the ring collar. Fig. 140 shows such a battery of three Bunsen's cells, with the parts somewhat drawn out from one another.

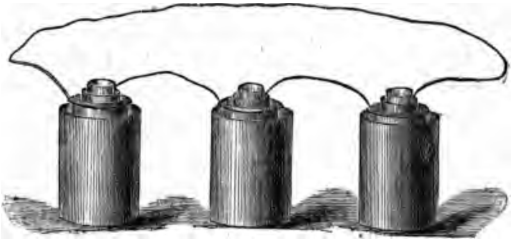

Fig. 140.

166. Of the comparative merits of the three forms of

battery—Daniell's, Grove's, and Bunsen's—which have just been described, or, rather, of their suitableness to various purposes, a few remarks may be made. For the most perfect constancy, where intensity is not requisite, or where abundance of room enables intensity to be obtained by a multiplication of the cells, some form of Daniell's (zinc-copper) is generally used. Where batteries are used in electro-plating * the uniformity and strength of the metallic deposit depends upon the uniformity of its rate of deposition (See Chap. III). Accordingly, some modification of Daniell's battery is used. The same is employed in the English telegraph. In an enormous system like that of the Central Telegraph Office in London, the fumes arising from the nitric acid cells would be a serious inconvenience; the expense of acid would also be considerable. By using a form of Daniell's, in which many cells are arranged together as a divided trough, great compactness is attained. The many thousands of cells there in use require replenishing only once in several months, and the products in the dead cells have a commercial value.

Grove's battery is generally used in this country for experimental or illustrative purposes, where a high intensity of the current is required: where much resistance has to be overcome, as in the electric light or electrolysis. The platinum foil is expensive but indestructible. The compactness of form of this battery is also a great advantage.

Bunsen's battery is used in Germany where Grove's is used in this country. It is cheaper, and has a slightly higher intensity, cell for cell. But it is clumsy in form. The batteries used in the electric telegraph in Germany and France are usually modifications of the zinc-carbon or Bunsen's battery.

167. Other Forms of Battery.—Certain other forms of battery may be here mentioned—forms which, though not now or yet in general use, are either of historical interest, or involve ideas which may hereafter be developed, or which are applicable for special purposes. Soon after the battery of Volta was described, Wilkinson devised a mechanical arrangement by which the whole of the plates of zinc and copper could be plunged at once, each pair into its respective cell of a divided trough, when the battery was required, and withdrawn when the battery was to be put out of use. Wollaston improved upon this device by doubling the size of the copper plates and bending them in the middle, so that the zinc sheet was surrounded by copper; the effect of this is to double the size of the plate, and so to double the quantity of electricity. Without at present considering the measurement of the resistance which the current experiences in the battery itself, we may assume that that resistance diminishes as the size of the plates increases—that is, as the vertical sectional size of the horizontal column of liquid in the cell through which the current has to pass increases, and also as the distance between the plates diminishes. Accordingly, if two very large sheets of copper and zinc are separated by a layer of felt, and a layer of felt being placed on the upper metal, the whole are rolled together and dipped in acid, the resistance is a minimum, and a strong current will pass between the metals connected outside the acid. Such is Hare's deflagrator, which shows great heating effects in imperfect conductors connecting its poles.

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* Magneto-electric currents are now extensively used where electro-*plating is carried on* very extensively. See Chap. V.

168. Cruikshank's Trough was one of the first successful efforts to introduce compactness of form into a liquid battery. Plates of copper and zinc are soldered together face to face in pairs; each resulting plate being thus composite. These plates form the divisions between the cells of a trough of baked wood or other non-conducting material, the zincs facing all one way and the coppers the other. At one end of the trough is a plate of copper, at the other a plate of zinc, as in fig. 141.

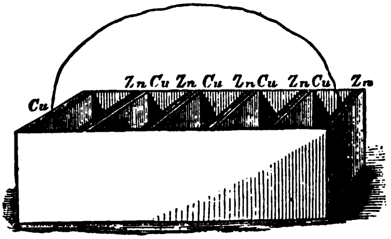

Fig. 141.

169. Smee's Battery.—The most successful attempt to procure a constant battery of only one liquid is exhibited in Smee's battery. We have seen how the hydrogen evolved at the copper pole of a zinc-copper battery acts injuriously to the current by masking the copper and sending a current in the opposite direction. If the + pole be made of platinum or silver, and covered with metallic platinum in a state of extremely fine division, the hydrogen evolved on it immediately and almost completely escapes. To cover the platinum plate with platinum it may be dipped in a solution of chloride of platinum and then strongly heated, or it may, when immersed in the solution of platinum, be connected for a moment with the zinc end of a voltaic cell while another piece of platinum is connected with the copper end, platinum is thus deposited (see Chap. III., Electrolysis) from the solution upon the platinum plate in an extremely fine state of division. As in Grove's battery, the platinum has opposite to both its faces amalgamated zinc. Walker's cell and battery differs from Grove's in having carbon instead of platinum upon which the finely divided platinum is deposited. If gas coke be used as the carbon, the hydrogen is evolved from its sharp points to a considerable extent without platinization.

170. **Davy's Battery or Cell.**—The cell devised by Marié Davy is a double liquid cell. Its poles are of zinc and carbon as in Bunsen's. The zinc is in contact with brine, and the carbon with sulphate of mercury. On joining the poles an action is established which we may most conveniently compare with the action of a Daniell's cell. Chloride of zinc is formed, which dissolves: the deprived sodium reacts as before, depriving its neighbouring molecule of chloride of sodium of its sodium, and so on until the porous cell is reached which divides the brine from the sulphate of mercury. Now chloride of mercury is formed, and the liberated sulphuric acid carries on the same series of decompositions followed by re-compositions until the carbon is reached; here the mercury is deposited, but there being no amalgamation or even cohesion possible, the liquid metal collects in drops and falls to the bottom. The solution of salt about the zinc should be weak. The solution of sulphate of mercury about the carbon should be saturated. As the sulphate of mercury is sparingly soluble in water, a considerable amount of the undissolved sulphate should be allowed to lie at the bottom of the carbon cell.

171. Leclanché's **Cell and Battery.**—This is a one-liquid cell. The elements are zinc and carbon, and the liquid a solution of chloride of ammonium. The zinc is in free contact with the chloride of ammonium. The carbon is in a porous cell which stands in the zinc cell; the space between the carbon pole and the wall of the porous cell is filled tightly with a mixture of carbon and peroxide of manganese in coarse powder. Chloride of zinc is formed, the separated ammonium immediately decomposes into hydrogen and ammonia, the latter of which at first dissolves in the solution and, when this is saturated, escapes as a gas. The hydrogen, meanwhile, after causing in the usual way successive decompositions of the contiguous molecules of chloride of ammonium, appears through the porous cell, and finds itself at last in contact with the peroxide of manganese, this oxidizes the hydrogen to water, being itself in the first instance reduced to the form of sesquioxide, according to the equation

$$Zn + 2ClNH_4 + MnO_2 = ZnCl_2 + 2NH_3 + H_2O + Mn_2O_3.$$

The ultimate condition of the manganese oxide is not known.

172. Gravitation Batteries.—Attempts have been made to dispense with the rigid porous wall, to separate the two liquids of a cell by placing the denser liquid beneath and allowing the two to mingle only by diffusion. Sometimes the mixing is further checked by the introduction of sand, sawdust, or some similar substance. C, fig. 142 is a copper plate at the bottom of an impervious vessel V. The copper plate is soldered to a gutta-percha covered copper wire A, which reaches above the liquid, the latter is water which is poured upon a mass of crystallized sulphate of copper which rests upon the copper plate B. Near to the surface of the liquid is the zinc element Zn also soldered to a gutta-percha covered wire D. The crystals of sulphate of copper dissolve and diffuse till the zinc is touched; sulphate of zinc is produced, which being lighter than the sulphate of cop-

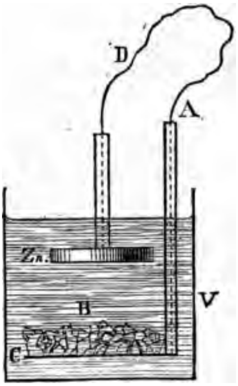

Fig. 142.

per, atom for atom, remains for the most part above. The action is otherwise precisely like that of a Daniell's cell. Before pouring in the water, moist sawdust or sand may be added until the vessel is nearly full, and then only sufficient water to thoroughly wet the whole. The zinc may then be laid on the top of the moist mass. This contrivance avoids the necessity which is experienced in a pure "gravity" cell of keeping the cell quite steady.

173. Schönbein's, Callan's, or the Maynooth Battery.—Iron, when plunged into the strongest nitric acid, or, still better, into a mixture of nitric and sulphuric acid, is not only not attacked (as it is when either or both acids are dilute) but is thereby thrown into such a state that it is not attacked when subsequently put into dilute acids. The iron so influenced is said to be "passive," and passive iron may be used as the electro-negative element (to form the + pole) of a voltaic couple. It is found, however, that the passive iron soon loses its peculiar property, especially if touched with less oxidizible metals. Hence in employing it as an element in a battery, the iron is kept passive by continual contact with the nitro-sulphuric acid. A porous cell is placed in a cast-iron cell—amalgamated zinc and dilute sulphuric acid (1 : 10). In the iron cell is placed a mixture of three parts by weight of the strongest nitric acid and one part of oil of vitriol. It is sometimes recommended to add a little nitric acid to the zinc-holding cell.

174. Chromic Acid Battery (Clark's).—The attempts which have been made to replace nitric acid by chromic acid, for the purpose of burning off the hydrogen, have not hitherto been attended with perfect success. Chromic acid itself is difficult to prepare in the pure state; but for the purpose in point it need not be pure. The chromic acid used for the battery is obtained—mixed with sulphate of potassium and free sulphuric acid—by dissolving bichromate of potassium in water and adding a large excess of oil of vitriol. The proportions recommended by Mr. L. Clark are 2 by weight of bichromate, 20 of water, and 10 of oil of vitriol. This is poured into a porous cell containing the carbon pole. The two are then placed in a glass vessel which is filled with *saturated* brine and contains the amalgamated zinc. The sodium released from the chlorine, which unites with the zinc, commences the series of decompositions so often described above, until it (or its representative hydrogen) meets with the chromic acid (CrO_3), which oxidizes it to soda, becoming thereby converted into sesquioxide of chromium (Cr_2O_3), which, together with the soda, unite with the sulphuric acid which is present in excess to form sulphate of chromium and sulphate of soda respectively, according to the equation—

$$6Zn+6NaCl+6H_2SO_4+2CrO_3=$$
$$6ZnCl+6H_2O+3Na_2SO_4+Cr_2 3SO_4.$$

175. Pulvermacher's and Stringfellow's Combinations.—In the former of these zinc wire and gilt copper wire, isolated from one another by one of them being covered, are wound round a piece of porous wood. The wires terminating in hooks may be hooked on to the ends of a second pair of similarly wound wires, and so on. A band or chain is thus formed, which, when moistened with vinegar or brine, or even with the moisture of the skin, sets up a galvanic current, which by the flexible and clean nature of the combination, may be readily applied to any portion of the body. A similar battery, of minute parts, is formed by soldering a flattened copper wire to one corner of a little zinc plate, and, after covering the plate with thin muslin, wrapping the wire spirally round it. A few such combinations are able to give rise, when moistened with spring water, to a current of considerable power.

176. In speaking of the necessity for amalgamating the zinc plates in order to obtain a uniform and maximum effect, mention was made of local currents brought about by the difference of hardness (Art. 163). By artificially hardening a piece of zinc, one may thus make a feeble battery or cell in which only one element and only one liquid enters. Cast zinc is less easily acted on than rolled zinc by dilute sulphuric acid. Hence, if pieces of cast and rolled zinc are joined by a wire, and plunged into dilute acid, the current circulates from the rolled to the cast zinc through the liquid, and hydrogen appears on the surface of the cast metal.

If a bar of copper is placed vertically in a glass vessel, and its lower end surrounded by a strong solution of sulphate of copper, the upper end being surrounded by dilute acid, brine, or even spring water, the upper portion will gradually dissolve away, and the lower increase by deposition of copper until the whole is transported into the sulphate of copper, the liquids remaining chemically unchanged. The corrosion of silver, when a drop of nitrate of silver is left upon it, or of copper, when sulphate of copper remains on it, is no doubt due to the same cause, namely, a difference of density of the metallic solutions at different parts setting up currents which tend to transport the metal from the less to the more dense parts.

177. Silver Air Battery.—The oxygen of the air held in solution in a single liquid cell, appears to determine the oxidation of a metal in the liquid which would not otherwise attack the metal, and this is especially the case when the more electro-negative metal is associated with the oxygen, and metallic communication is established between the two metals. Thus fig. 143 shows an arrangement by which a current is established between silver and copper in a solution of nitrate of copper, when the silver is freely exposed to the air. A is a silver dish supported horizontally in a solution of nitrate of copper. Upon the tray A is a heap of metallic silver, B, in a fine state of division, such as is obtained on reducing it from solution by contact with a displacing metal. C is a sheet of copper beneath the silver, and parallel to it. The current passes through the liquid from C to A. The copper plate becomes corroded, being converted into suboxide of copper (Cu_2O). For this action oxygen is necessary, for if the air be displaced by diffusion, on surrounding the whole with carbonic acid, the action dwindles and stops. The chemical change is represented by the equation—

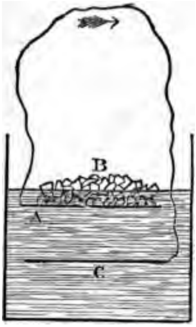

Fig. 143.

$$Ag + O + Cu2NO_3 + 2Cu = Ag + Cu2NO_3 + Cu_2O,$$

in which it is seen that the silver and nitrate of copper remain unaltered.

178. Cells and Battery of like Terminals.—By selecting suitable liquids, it is possible to construct a battery of two metals in such a manner that the two poles are of like metal. Such batteries are of great interest, inasmuch as they touch the question concerning the contact theory of electric excitement. Fig. 144 shows a few cells of such a battery devised by Mr. Fleming. The liquids are nitric acid and pentasulphide of sodium in alternate cells. The metals are copper and lead. Each metal is bent so as to connect two neighbouring cells. It is clear that on using an even number of such cells the terminals are both copper. In nitric acid lead is + to copper, so that the + current passes through the liquid from the lead to the copper. In the sulphide of sodium, the copper is + to the lead, so that the current passes from the copper to the lead, or again from right to left, and so on.

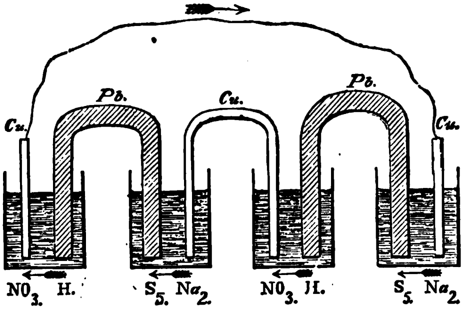

Fig. 144.

Consequently all the pairs send the current in the same direction, and the combination gives a current outside the battery, through a copper wire from left to right. In this battery no two dissimilar metals are in metallic contact, and yet four of such cells may easily at first produce a tension equal to that of a Daniell's cell.

CHAPTER III.

ELECTROLYSIS.

179. We have seen in the last chapter how the completion of the connection between the poles of a cell affects the arrangements of the chemical elements in the cell, causing, to refer to the simplest case, hydrogen to be evolved from the surface of copper instead of at that of the zinc, when the two are placed side by side in acidulated water. And we have noticed that the connecting wire acquires, during the action of the cell, certain properties (Art. 139, *et seq.*). Let us now break the connecting wire, and rejoin the ends by inserting between them various substances, and arming the ends of the wire differently. Examined in this manner, matter at once falls into very distinct classes. Gases and vapours of all tensions and of all kinds, the most perfect vacuum, hydrogen, air, vapour of mercury, etc., all completely refuse to let the current pass through them. The poles from a Grove's battery of some hundred cells, when brought about the thousandth of an inch apart, are, it is true, connected by a spark, and subsequently become incandescent, and the current passes. But, as we shall see, this current-passage is more properly a convection than a conduction of the current, the metallic particles of the poles are torn from one pole and carried to the other, and so the interval may be only said to conduct in the sense that it does not offer substantial resistance to the mechanical motion of the matter. Turning next to solids, we find them divided into conductors and non-conductors. Simple metals conduct surpassingly well, though, as we shall see, they differ among themselves very considerably when we consider *Resistance* (Chap. IV.). Metallic alloys, when there is no alteration in volume during mixture, conduct with a facility intermediate between those of their constituents. Next come metallic sulphides and oxides, salts, etc. The non-metallic solid elements are, with few exceptions, non-conductors, as are their combinations. Of liquids there are three classes: (1) Those which conduct freely without themselves undergoing any change; such are the molten metals, mercury, and their alloys. (2) Those which entirely refuse to conduct, and are therefore unaffected when between the poles. (3) Those which conduct the currents, and at the same time suffer decomposition. Solids which conduct undergo no chemical change. Non-metallic liquids which conduct always undergo decomposition.*

180. Such decomposition is called Electrolysis. The liquids which undergo electrolysis are called Electrolytes. The terminals of the poles of the battery or cell which excites the current, and which are in contact with the electrolyte, are called electrodes. The electrode in connection with the + pole (– metal, platinum, carbon, etc.) of the battery or cell, is called the Anode. The electrode in connection with the – pole (+ metal, zinc, etc.) of the cell or battery, is called the Kathode. The products of electrolysis, which appear at the kathode, are called Kations; those which appear at the anode are called Anions. Thus (fig 145), let X be a cell of dilute sulphuric acid, in which are the pieces of zinc (Zn) and copper (Cu). Let the copper wires from Zn and Cu be brought into the liquid A in the vessel B. Then we will

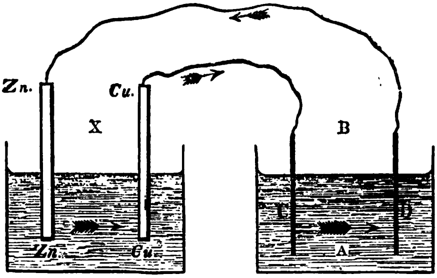

Fig. 145.

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* The exceptions to this rule are, when exceedingly feeble currents are employed. Such cases are considered under *Resistance* (Chap. IV.).

suppose the liquid A to be decomposed by electricity or electrolysed. It suffers electrolysis. A is the electrolyte. The current enters A by the anode C, and leaves it by the kathode D. The product of decomposition which collects at C is the anion, that which collects on D is the kathion.

181. Electrolysis of Water.—Perfectly pure water is difficult to electrolyse: it may be ranked with non-conductors, but sulphuric acid diluted with twenty or thirty thousand times its own volume of water conducts freely, and is therefore decomposed abundantly. The visible products of the electrolysis of such a mixture are the elements hydrogen and oxygen, as though water alone had been decomposed; and it is true that the quantity of free acid in the cell is the same after as before the passage of the current. Almost all the water may disappear in the form of its elements leaving the acid as before. The experiment is shown in fig. 146. A glass vessel V, having two holes in its base, stopped with corks A, B, about an inch and a half apart, is partly filled with "battery" acid (1 of oil of vitriol to 12 of water).

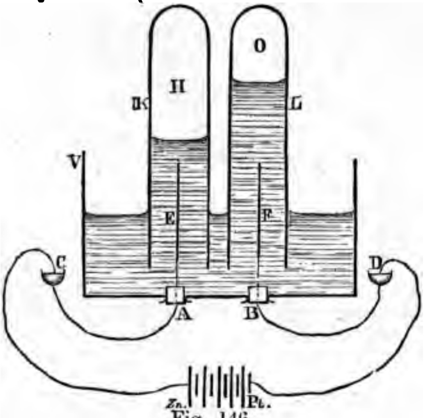

Fig. 146.

Through the corks A and B pass two stout copper wires, terminating outside the vessel, in two little iron cups containing mercury C, D. Inside the vessel the copper wires *are armed with* two strips of platinum-foil E and F (electrodes). Two glass tubes, K and L, being filled with the same acid, are inverted into the vessel V, so that they remain full of liquid, and have their mouths over the electrodes respectively. A battery of four or five Grove's (or Bunsen's) cells has its poles Zn and Pt connected with the two mercury cups C and D respectively. Straightway bubbles of hydrogen appear on the surface of E the kathode, and bubbles of oxygen on the surface of F the anode. These bubbles rise in the respective tubes and collect. The ratio of their volumes remains constant, namely, two volumes of hydrogen to one of oxygen. This at once appears, if the tubes are of equal *calibre*. However long the electrolysis continues, this ratio is preserved. This is the ratio by volume of these two elements in which they exist in water. If the two gases, thus separately collected, be mixed and exploded, no residual gas is left. They may be collected together, the mixture forming what is called detonating gas, which is used to increase the explosion of difficultly exploding gases in gas analysis. If the electrodes are both made of iron, copper, lead, etc., that is, metals which are easily oxidized, the hydrogen will appear as before at the kathode E, but the oxygen which appears at the anode F at once combines with the metal forming oxide of iron, copper, lead, etc., which unite with the acid to form sulphates. In the case of the two first of these metals the sulphate is soluble, so that the anode will go on corroding as long as any metal is left. The sulphate of lead being difficultly soluble, and a bad conductor, will soon coat the anode with an impervious crust, which will stop the conduction, and so the electrolysis. The first portions of the gas collected are when platinum poles are used not exactly in the correct proportion. Hydrogen fails. This is due to the "occlusion" of hydrogen by platinum under these circumstances. The hydrogen is absorbed by the platinum. Very soon, however, the metal becomes saturated, and the exact combining ratio is observed.

In fact the electrolysis of water gives one of the best means for obtaining hydrogen in a state of absolute purity. Fig. 147 shows a cylindrical glass vessel A, having a stout platinum wire C fused through the glass near the foot. In this glass is placed some zinc and mercury, so as to touch the inner end of C. Battery acid is poured in so as nearly to fill the cylinder. Through the cork E passes a platinum wire B, encased by fusion in a glass tube F, where it passes through the cork, and connected inside the cylinder with a strip of platinum foil K, which is as near as convenient to the surface of the mercury-zinc. The cork E also carries a bent tube G, provided with bulbs containing oil of vitriol.

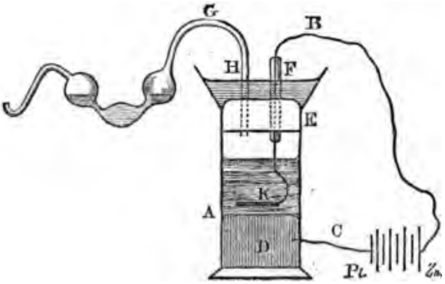

Fig. 147.

In order to make the cork E perfectly water-tight, a little water H is poured above the cork. C is connected with the + (Pt.) and B with the – (Zn) end of a battery of a few cells. The oxygen evolved on the mercury-zinc oxidizes the latter metal, and dissolves it as sulphate of zinc. The hydrogen evolved on K escapes through G, and, after drying by the sulphuric acid, is delivered in a state of the greatest purity. On reversing the current, that is, on connecting B with Pt., and C with Zn, hydrogen is evolved from D, and oxygen from K. The pure, mixed gases may after a few minutes be collected.

182. We shall see subsequently that the resistance to electricity which passes through a conductor, whether electrolyte or not, is directly proportional to the distance apart of the ends of the conductor (its length), and inversely proportional to the sectional area of the column traversed. Accordingly, with a battery of a given strength, the nearer the electrodes are together, and the larger they are, the greater the quantity of electricity which passes through the electrolyte, and greater, accordingly, the amount of electrolysis effected. If, indeed, the resistance be heightened by making the electrodes very small, mere platinum points, the hydrogen is evolved as before, but the oxygen both oxidizes itself and hydrogen, forming ozone (O_2O) and peroxide of hydrogen (H_2O_2).

183. The fact that an acid (or alkali or salt) must be added to pure water in order to make it conduct, forces upon us the consideration of the condition of such acid during the electrolysis of the liquid. For this examination we may take a cell (fig. 148) and divide it in two by a porous diaphragm D, fill the two halves equally with battery acid, and electrolyse as in Art. 181. Let the electrolysis be carried on till a large volume of the gases is collected. On measuring the gases it is easy to calculate the weight of water which has been decomposed. On examining the two cells it is found that though the total quantity of sulphuric acid remains unchanged, it has collected mainly around the anode, leaving the cell in which the hydrogen was evolved poorer in acid. It might be thought from this that the sulphuric acid alone underwent decomposition, and that for every equivalent (two atoms) of hydrogen which appeared at the − pole (kathode) an equivalent of oxygen (one atom) and an equivalent of anhydrous sulphuric acid (SO_3) appeared at the + pole (anode), which latter substance, by combining with the water present, became H_2SO_4. Experiment, however, shows that for every equivalent of hydrogen at the − electrode, only $\frac{1}{3}$ of an equivalent of H_2SO_4 appears at + electrode. And hence it would seem that the current is conveyed by and decomposes the water, as well as the sulphuric acid, and, indeed, in the proportion of three-quarters of the current for the water, and one-quarter for the sulphuric acid. We shall return to the consideration of this point after the discussion of the electrolysis of other compound liquids.

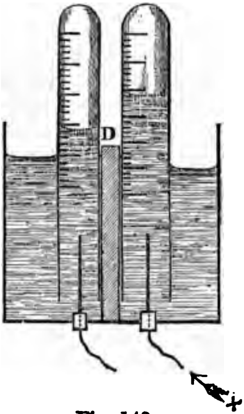

Fig. 148.

184. Electrolysis of Salts.—For our present purpose we may define a salt as a chemical compound containing a metal. Such a body may become liquid by simple fusion, or by solution in some medium. Fused salts invaribly suffer decomposition by the current, and dissolved ones do the same when the solvent is water. The most convenient salt to take when the object is to procure the metal which it contains by electrolysis is generally the chloride. The metals of the alkalis, however, potassium and sodium, may be obtained from their hydroxides KHO and NaHO. A piece of such a solid caustic alkali is placed upon platinum-foil and very slightly moistened. The foil is connected with the + electrode of six or eight Grove's cells, and a platinum wire connected with the – electrode is made to touch the upper surface of the alkali. Oxygen is evolved from the lower surface. The upper surface melts, and the platinum wire becomes surrounded by small globules of the metal, which, when the mass has become cold, may be detached from it under paraffine oil. This method of preparing the metals of the alkalis is of great historical interest, but is superseded now by purely chemical processes.

185. To obtain metallic calcium a mixture is made of one equivalent of chloride of calcium, one of chloride of strontium, and one of chloride of ammonium. These are heated in a porcelain crucible, and, as usually happens, the mixture has a lower melting point than either of its constituent chlorides (the chloride of ammonium, heated by itself, volatilizes without melting). A piece of dense carbon dips into the molten mass and serves as the anode. A piece of pure iron wire, dipping but little beneath the surface, serves as a kathode of 8 or 10 Grove's cells. The chlorine evolved on the carbon does not attack it as it would platinum or any metal. The calcium collects on the iron, which is from time to time removed. Lithium may be obtained in a similar manner from chloride of lithium and magnesium. On account of the superiority of the specific gravity of the magnesium over that of the fused mixed chlorides, the – pole may be at the bottom of the fused mass. Fig. 149 shows a method of preparing the metal in which the chlorides are fused in a *clay tobacco* pipe, up the the stem of which an iron wire is thrust to serve as the – pole or kathode. The anode is a piece of dense carbon.

186. Chloride of silver, when fused, is decomposed by the current. If both electrodes are of metallic silver the + electrode combines with the chlorine which is developed upon it at exactly the same rate as the silver is deposited upon the – pole. Accordingly the fused salt appears to remain unchanged, and to be simply traversed by the silver, which also remains unchanged in quantity though changing in position.

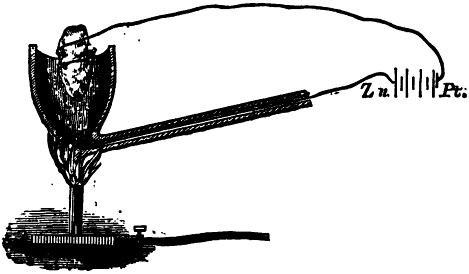

Fig. 149.

187. Concentrated aqueous solutions of the metallic chlorides behave generally like the fused salts. Chlorine appears at the +, and the metal at the – electrode. In the case of the metals of the alkalis and alkaline earths, the liberated metals quickly oxidize at the expense of the water, liberating their equivalent of hydrogen, unless, indeed, the – electrode be mercury, in which case the metal dissolves in the mercury, and is kept by contact with it from oxidation, sharing its negativeness. In this way amalgams of barium and calcium with mercury have been got, from which the mercury can be expelled by heating in a current of hydrogen. Chromium and manganese have been got from solutions of their chlorides by a slight modification of the method just described as coherent, brittle, metallic films, upon a platinum kathode.

188. Ammonium Amalgam.—Soon after the reduction of the alkaline metals, attempts were made to establish the physical analogy between the quasi metal ammonium and the alkaline metals corresponding to their well marked chemical analogy. If a weak solution of chloride of ammonium

(NH_4Cl) is submitted to electrolysis chlorine appears at the +, and a mixture of H and NH_3 at the – electrode. If, however, the chloride of ammonium be poured upon mercury, and the latter be connected with the – electrode, the mercury swells enormously without losing its metallic lustre. If a single drop of mercury attached to a platinum wire* serve as the – electrode in the chloride of ammonium solution, the mercury becomes grey and almost loses its metallic lustre, increasing to the size of a pea. The substance certainly contains H and NH_3 in the proportion in which they exist in NH_4; but whether the NH_4, if it exist in this substance, would have by itself the physical properties of a metal, is by no means decided. The so-called amalgam may be kept for a long time unchanged if kept at or below 0°C. On standing after removal from its electrode, especially if warmed, and more especially if in contact with water, it is quickly resolved into Hg, H, and NH_3. It is noteworthy that none of the compound chlorides of ammonium, such as chloride of methylamine, produce a similar amalgam. If the solution of chloride of ammonium be warm and saturated, the chlorine set free at the anode attacks the chloride of ammonium, forming the dangerously explosive chloride of nitrogen.

189. Electrolysis of Aqueous Solutions of Salts in General.—The electrolysis of dilute sulphuric acid, described in Art. 181, may be taken as the type of the electrolysis of metallic salts in all cases where secondary reactions are not set up, that is, where the ions or travelling elements of decomposition do not react upon the general mass of the electrolyte at the region of their liberation. As examples of salts showing this difference, we may take sulphate of copper and sulphate of sodium. On electrolysing sulphate of copper ($CuSO_4$) dissolved in water in an undivided cell between platinum poles of not too small a size, nothing but copper appears at the – electrode, while oxygen is set free at the + electrode: the whole becomes acid. If the electrolyte be divided into two by a porous diaphragm, the copper gradually disappears from the solution at the kathode end as it is deposited, while sulphuric acid appears at the anode, where the oxygen is being liberated. But (as in the case of the sulphuric acid and water) the quantity of sulphuric acid there appearing is less than equivalent to the liberated oxygen. This appears to show that water is simultaneously decomposed, and that the hydrogen liberated at the – electrode, or kathode, at once reacts upon the sulphate of copper to reduce it and add the metal to the kathode and form sulphuric acid. So that even here secondary action is not wholly absent. On electrolysing sulphate of sodium (Na_2SO_4) in water, the inverse secondary action takes place. The oxygen and hydrogen are evolved at the respective poles in equivalent quantities (16 : 2 by weight, 1 : 2 by volume) as though water alone had been electrolysed; but if the porous wall be introduced, the kathode cell becomes alkaline, and the anode acid—showing that the sulphate of sodium has been decomposed, and that the hydrogen is in part to be reckoned to the action of the sodium on the water.

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* See Appendix, X.

$$Na+H_2O=NaHO+H.$$

190. The electrolysis of hydrate of potassium or sodium in dilute aqueous solution also gives a result as though water alone had suffered decomposition.

$$\begin{array}{rl} & \qquad\quad\text{Anion. Kation.} \\ & 2NaHO=2Na+2HO \\ \text{and } & 2Na+2H_2O=2NaHO+H_2 \ldots\ldots\ldots\ldots\ldots(1.) \\ \text{and } & 2HO+H_2O=2\,H_2O+O \ldots\ldots\ldots\ldots\ldots(2.) \end{array}$$

In words, the ions are sodium and peroxide of hydrogen, though neither of these appear, because the sodium decomposes water, liberating hydrogen (equation 1), and the peroxide of hydrogen, together with water, forms more water, and liberates oxygen (2). Accordingly, if the electrodes are separated by a porous wall, the anode cell becomes dilute, and the kathode cell more strongly alkaline.

191. If the electrodes are very small, and the current strong, the whole of the strength is concentrated on a small space, and the result is that the tension is so increased that both sodium and salt are decomposed together, and the bubbles of hydrogen disturb the metallic deposition.

192. The development of free acid and free alkali, during the electrolysis of sulphate of sodium and similar salts, may be well shown by dividing the electrolytic cell into two by a porous wall, and adding a little solution of litmus to both divisions. A drop or two of acid is added to one cell, and a drop of an alkali to the other. The first becomes red, the second a clear blue. On plunging the platinum kathode into the acid or red solution, and the anode into the blue or alkaline solution, a change soon manifests itself. The red becomes blue and the blue red, owing to the free hydrate of sodium developed in the former and the free sulphuric in the latter. On reversing the current the original colours are restored.

193. Hydrochloric acid gas dissolved in water forming the liquid usually called hydrochloric acid, yields, when electrolysed, hydrogen at the – electrode, and either chlorine or oxygen, or a mixture of these gases, at the + pole, according to the strength of the acid. Very dilute acid yields nearly pure oxygen. Strong acid of the strength which it generally has in commerce, or that which is got by distilling the commercial acid, and which contains about 20 per cent. of HCl gives pure chlorine at the anode. By an arrangement similar to that described in Art. 181 for the preparation of detonating gas, the elements of H and Cl are obtained in exactly the proper proportion to form HCl. It is necessary, however, to use as an anion a carbon electrode, since chlorine liberated upon any metal whatever attacks it. If more dilute hydrochloric acid is electrolysed, the freed chlorine is oxidized by the freed oxygen to chloric and perchloric acid.

194. The electrolysis of the salt of a metal which is not easily oxidized is beautifully shown when a weak solution of acetate of lead is electrolysed between platinum wire electrodes by a couple of Grove's cells. Such a cell being illuminated from behind may be imaged on a screen, and presents the appearance shown in fig. 150. Bubbles of oxygen arise from the + pole, while from the – fern-shaped growths of metallic lead are seen to grow and shoot across the field.

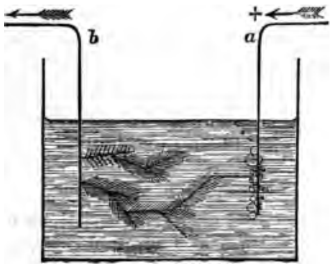

Fig. 150.

The first "fronds" on touching the oxygen are burnt off at their tips, but by-and-bye others follow in such mass that the interval is bridged over, metallic communication is established, and electrolysis ceases. If, before this ensues, the current is reversed, that is, the kathode is converted into the anode, and *vice versâ* by altering the connections with the battery, the oxygen ceases on *a* and the metallic growth commences there. The lead upon *b* is seen to dissolve away from the points backwards. The oxygen which is emancipated then unites with the lead, and the oxide of lead so formed dissolves in the free acetic acid, which was one of the products of the original electrolysis, and which is present at any given time in quantity exactly equivalent to the quantity of metallic lead free at the same time. It is only when the whole of the lead on *b* has been thus dissolved off that bubbles of oxygen begin to appear at that pole. It is necessary that the battery power be not too great, else hydrogen is evolved at the kathode along with the lead, owing to the simultaneous decomposition of the water in such quantity that it does not meet with sufficient lead in its immediate neighbourhood to reduce, and some of the gas escapes as bubbles, which interfere with the regularity of the metallic deposit. Peroxide of lead is sometimes formed on the anode.

195. Silver, when deposited by electrolysis from a solution of nitrate of silver (about 15 grains to the ounce) appears on the kathode as long, delicate needles. If the solution be rather strong, and especially if the action be reversed two or three times, a solid growth appears on the anode along with the gaseous oxygen. This is dioxide of silver (Ag_2O_2); it appears as black, extremely attenuated needles of very rapid growth and great brittleness. They shoot out, and encountering the growth of silver from the kathode, are quickly broken. Many of them fall, indeed, by their own weight, for they have no substantial connection with the anode.

196. Copper and iron and gold, when deposited under similar conditions, appear as rounded fungoid masses of no distinct crystalline form. The indescribable beauty of these phenomena of electrolytic deposition may be readily studied under an ordinary achromatic microscope. A drop of the metallic solution being placed on the object plate of the microscope, two of the finest pieces of platinum wire are introduced into it, and then connected with a couple of small Grove's cells. The process is best seen when the field is viewed by both transmitted and reflected light.

197. By means of electrolysis an insight is got into the molecular construction of certain compound bodies which it would be otherwise difficult to attain. Thus, acetate of potassium $KC_2H_3O_2$ is divided by electrolysis into $K + CO_2 + CH_3$: the potassium of course reacting upon the water present, and forming hydrate of potassium under the liberation of hydrogen. The carbonic acid and methyl appear at the anode, and the former may be removed by caustic potash. It was thus that the body methyl was first obtained, and the constitution of the acetates determined. This view of their constitution was confirmed by the synthesis of the acetate of sodium by the direct union of carbonic acid with a compound containing zinc, sodium, and methyl, got by treating zincmethyl with sodium. Valyl (C_4H_9) has been similarly got by the electrolysis of valerate of potassium.

The constitution of the sulphovinate of potassium has been determined in like manner. The formula of this body is

$$KC_2H_5SO_4$$

and the question whether the molecule of ethyl (C_2H_5) is electro + or electro − in regard to the whole body; in other words, whether the salt contains a double base or a double acid appears to be decided in favour of the latter by electrolysis; for on electrolysing the salt between zinc electrodes, or with the kathode of platinum and the anode of zinc, hydrogen is evolved at the kathode and sulphovinate of zinc is formed at the anode.

198. Chemical Decomposition by high tension Discharge.—We may now add one more link, connecting high tension or frictional electricity with voltaic electricity, and so confirm the notion that the two kinds are essentially identical. Let two fine platinum wires be fused into two glass tubes, so that their ends only just peep out of the glass (fig. 151), and let one be connected with the + and the other with the − conductor of an electric machine. Let the two be immersed in well-boiled water slightly acidified. On sending sparks *across the* interval, hydrogen appears at the pole connected with the – conductor, and oxygen at that connected with the prime conductor. The ratio of the two gases is, however, far from that in which they occur in water, for the volume of the hydrogen is about three times instead of being exactly twice that of the oxygen. Bearing in mind, however, that we are here dealing with high tension electricity, that is, with a kind to which the galvanic current approaches when the resistance is great and the poles small, we cannot but admit that the deficiency of free oxygen may be reasonably attributed to the formation of ozone or peroxide of hydrogen (O_3 or H_2O_2) as we found to be the case when voltaic electricity passed between very small electrodes.

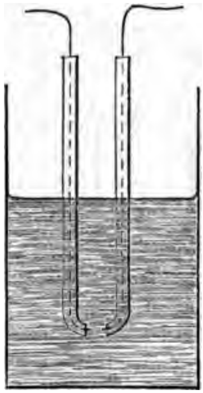
Fig. 151.

199. This relation is further confirmed by making a series of sparks pass along a strip of blotting paper one-half of which is coloured blue by litmus and the other yellow by turmeric, the whole being isolated on a glass plate. If the + conductor be in contact with the litmus, and the – with the turmeric, the former turns red and and the latter brown when the whole is moistened with sulphate of soda. Actual contact with the conducting wire is not essential. The wires may be sharpened and brought within an inch of the ends of the papers. The point discharge which then ensues effects the same decomposition of the sulphate.

200. Electric Osmose, and Migration of the Ions.—Let a narrow glass cell A (fig. 152) be divided by a wall of porous earthenware B, and let electrodes of platinum-foil C and D be connected with Zn and Pt, the respective poles of a 10-cell Grove's battery. Place pure water in the cell A, so that it stands at exactly the same level in both divisions. Scarcely any gas will be evolved, the water being so bad a conductor. But in the course of a few hours, the water around the – pole will be found higher than that around the + pole (2). With dilute sulphuric acid, or sulphate of copper, the amount of electrolysis is very much greater, but the

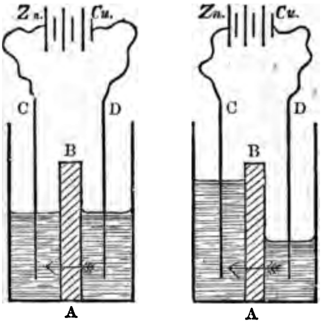

Fig. 152.

difference of level is found to be less, while with alcohol and other liquids, which conduct even worse than water, the passage towards the – pole is greater. A series of exact experiments have been made with the apparatus shown in fig. 153, which exhibits all the parts as though they were transparent. The outer cylinder A is open at the top. B is the anode in the form of a cylindrical sheet of platinum (or in the case of alcohol, copper). C is a cylindrical porous earthenware cell, fastened above to a short cylinder of glass E of the same size, which carries a cork F.

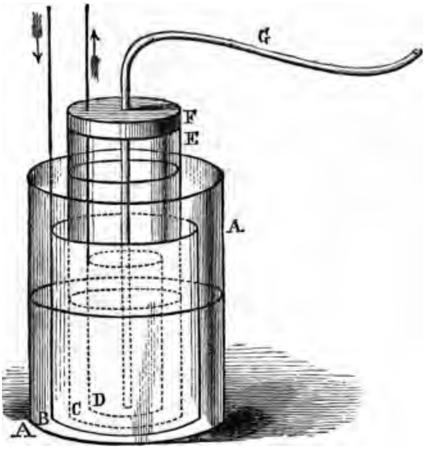

Fig. 153.

Through the cork F passes a platinum wire, protected from *contact with* the cork by being fused into a glass tube, and carrying below the copper or platinum kathode D. Through the cork F also passes a tube G, whose inner end dips into the liquid in the porous cell. On connecting the electrodes with the battery, as indicated by the signs, the current passes from B to D, and the liquid moves with it. The whole of the porous cell and glass cylinder, up to the cork, and the tube G, being perfectly full, the quantity of liquid which escapes from C is the same as that which has been moved by electric osmose. The gas is evolved in the case of alcohol or sulphate of copper, and an exceedingly small quantity in the case of water: such gas (H) may be collected and measured if necessary. It is found that the amount of electric osmose is proportional to the current strength of the battery, and that it is also proportional to the resistance of the liquid. The total quantity of electricity which passes through the cell may be measured by interposing a cell of sulphate of copper in the circuit, and weighing the quantity of metallic copper deposited upon the kathode of the interposed cell. This method of determining current quantity will be considered in Chap. IV.

201. The migration of the ions during electrolysis is measured in the following way:—A and B (fig. 154), are two similar cylindrical glass vessels for receiving the liquid to be examined. These being filled with the liquid, a syphon tube D is inserted so as to connect the two, and the air is drawn out of D′ until it is full; the tap K is then turned off, so that the syphon remains full, and the level of the liquid in A and B is of course the same. C is a cell of sulphate of copper, having two platinum electrodes, one of them (E) being

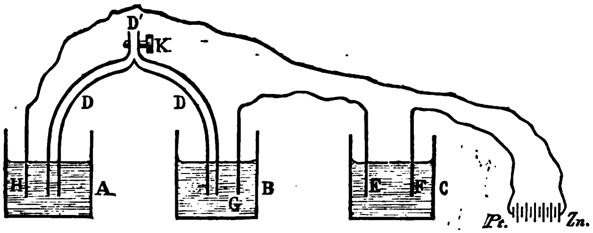

Fig. 154.

of known weight. H and G are also platinum electrodes, and the whole are connected together and to the battery Pt, Zn, as the figure shows. The current passes from Pt to F, to E, to G, through the syphon to H, and so to Zn.

After the current has passed for some hours it may be disconnected, and the tap K opened, whereupon the liquid in each leg of the syphon falls into its respective vessel. If A and B are filled with sulphuric acid and water (Sp. Gy. 1·116), it is found that for every grain of copper deposited on E, there are 0·2754 grains of sulphuric acid (H_2SO_4) migrated to the cell C, or for each equivalent of copper there have passed 0·18 equivalents of H_2SO_4. On substituting hydrate of sodium, NaHO in solution (of the Sp. Gy. 1·06), for one equivalent of deposited copper there are found to be 0·16 equivalent of sodium (or hydrate of sodium) transposed to A.

202. Let now both A and B be filled with sulphate of copper of the specific gravity of 1·09. It has been found that for every equivalent of copper deposited on E (or H), 0·18 of copper, as sulphate of copper, had passed into A. If the electrode G be of copper, its being oxidized and dissolved caused as much as 0·36 equivalent of copper to pass as sulphate into A, for every equivalent of copper deposited on E or H. More copper is therefore always deposited on H than reaches A by the travelling of the sulphate, and this is true whether G be of platinum or copper. If G be of platinum both cells lose in dissolved copper, because in A more copper is deposited than reaches that cell by travelling through the syphon; while there is nothing to replace the loss which B thus experiences. If, now, G be of copper, the liquid in B becomes richer in copper as the electrolysis proceeds, because for every equivalent of copper which is deposited on H, an equal amount is dissolved off G, and this is not counteracted by the lesser quantity which travels through the syphon.

203. Electro-plating or Galvano-plastic.—The covering of a body with metal by the galvanic current, is usually effected from one of two purposes: either by protecting a baser metal with a nobler one to shield the former from corrosion, and to give to the whole the appearance of being made out of the nobler metal. This may be called electroplating. Or by depositing a coat of metal on one object to obtain an exact metallic impression of the object. This may be called distinctively galvano-plastic. For the first of these —electro-plating—the object is only effectively attained when the deposited coating is firmly fixed upon the object; for the latter, subsequent separation must be kept in view while preserving such close contact between the coating and the object, that the finest lines of the original are reproduced.

204. It is of course essential that the surface of the body which has to receive the electro deposit should be a conductor. Metallic objects to be plaited should be scoured with caustic soda to remove grease spots, then with water to remove the alkali, and lastly, they should be momentarily dipped into nitro-hydrochloric acid to remove any metallic oxide, and immediately plunged into clean water, which should be renewed a few times. The roughness of the surface produced by the corrosive action of the acid is favourable to the adherence of the film. Let us suppose that it be desired to plate with silver a copper fork. A solution is made consisting of 100 parts of water (by weight), 10 parts of cyanide * of potassium, and 1 part of cyanide of silver: a clear solution is thus obtained, which is placed in a jar A (fig. 155). A metal rod B is placed across the rim of the vessel A, and from this the fork is hung by a metal wire which may be covered with wax all over, excepting where it is in contact with B and the fork. C is a rod similar to B, and from it is hung a silver plate D by means of a silver wire. B is connected with the Cu and C with the Zn poles of a Daniell's cell having large surfaces, so that there may be as little resistance as possible; and to this end the connecting wires are as short and thick as convenient. Silver is deposited upon the fork, and the released cyanogen dissolves a precisely equal quantity of silver from the + electrode, which is the silver plate. Hence the liquid remains from first to last of uniform strength. The fork is from time to time turned, so that back and front are in their turn nearest to the + electrode, for the deposition is thickest on the side nearest to that pole. If spots appear on the fork where the silver is imperfectly deposited, it is taken out and the parts scoured with clean fine sand and water. The attachment of the wire to the fork is from time to time shifted. In the course of one or two days, depending on the strength of the Daniell's cell, the process may be complete. As a rule when—as in the above case—the exposed surface of the deposit should be smooth, it is advisable to employ an alkaline solution. Copper, for instance, in a solution of nitrate of silver covers itself with an incoherent film of silver which is porous, and this independent action interferes with the consistency of the electro-deposit. A few drops of sulphide of carbon (CS_2) stirred up with the double cyanide for some unexplained reason causes the silver deposit to be formed with a bright surface. The more gradually the deposit is formed the tougher and softer it is.

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* Or ferrocyanide of potassium.

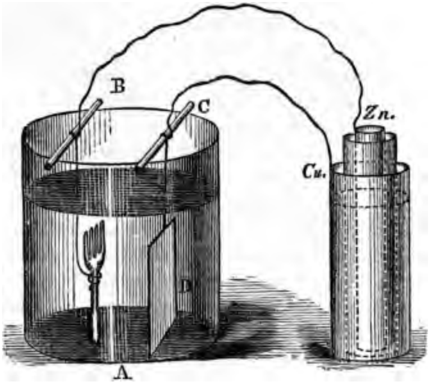


Fig. 155.

205. The electro-deposition of gold is generally effected from one or other of the following solutions:—the double chloride of gold and sodium dissolved in soda; chloride of gold dissolved with ferrocyanide of potassium; sulphide of gold dissolved in sulphide of potassium. The most generally useful solution contains 1 part (by weight) of dry chloride of gold, 2 of ferrocyanide of potassium, and 100 of water. This solution serves for gilding silver, copper, brass, bronze, *German silver*, steel, and iron. To gild tin, the latter metal must first receive a coating of copper. The deposition of both silver and gold is accelerated by warming the bath in which the electro-plating occurs. To electro-plate with platinum, a solution is made of chloride of potassium and platinum dissolved in caustic potash.

206. Copper, lead, tin, and zinc are also advantageously deposited from alkaline solutions when, as in the case of electro-plating, the metallic film has to adhere. The double cyanide of copper and potassium; the plumbate of potassium (got by digesting litharge in caustic potash); stannate of potassium or tartrate of potassium and tin; zincate of potassium (oxide of zinc dissolved in caustic potash), are the solutions of the metals most generally used. Iron and nickel are generally deposited from double tartrates of the metal with potassium. Nickel so deposited is considerably used at present for covering and protecting iron and steel from oxidation. Electro-deposited iron is remarkably pure from the substances which usually contaminate it (sulphur, carbon, silicon, and phosphorus), but contains a considerable quantity of dissolved ("occluded") hydrogen which is expelled by heat.

207. Leaves, flowers, insects, and other perishable bodies may be electro-plated, and, if the deposit be not too thick, much of the beauty and character of the original is preserved. A leaf dipped into a solution of nitrate of silver, and nearly dried, and then plunged into a solution of phosphorus in bisulphide of carbon, or exposed to the phosphorous acid arising from phosphorus exposed to the air, becomes coated with a thin film of metallic silver, the metal being reduced by the phosphorus or phosphorous acid. This film, thin as it is, suffices to convey the current and make the whole surface conductive, so that on connecting any part with the − pole of a battery, and plunging into one of the metallic solutions above described, while the + pole is made of the same metal, a deposit of metal ensues. Such coatings, if sufficiently thick to bear handling, are necessarily destitute of the finer lines of the original. In some cases, however, the original substance may be removed by burning or an acid without destroying the metal coating, and the latter may then serve as a mould for casting, or for a second metallic deposit effected electrolytically.

208. In a variety of cases the object sought is not to permanently cover the body (electro-plating) but to obtain a copy of it, either a negative (*i.e.*, an *intaglio* from a *relievo* or *vice versa*) or a true, positive reproduction. In all cases where the original is not "undercut," as in tool engravings (not etchings) and *bassi relievi*, such impressions are easily taken without injury to the original. We will suppose that the problem is to obtain a copper copy of a bronze coin. A copper wire is wrapped round the edge of the coin tightly. The wire and the back of the coin are covered with varnish or wax. The face of the coin is thoroughly cleaned, and brushed over with a dilute solution of potash, or slightly warmed, or exposed for a moment to iodine vapour. Hereby it is slightly tarnished, and the film subsequently deposited on it does not form absolutely one piece with the original. It is then made the − electrode in a solution of copper (Art. 204), the anode being also of copper. After two or three days the film of deposited copper is sufficiently thick to bear detaching. A copper negative is thus obtained, which, on being similarly prepared, receives a deposit, which, when detached, is an exact counterpart of one face of the original coin. The first or negative deposit may, of course, be used as a mould for taking castings in. It may receive paraffine or plaster of Paris, etc.

209. In many cases antique coins are considered too precious to bear the handling above described. A negative mould of them may in such instances be taken in plaster of Paris or gutta-percha softened in warm water. In using the gutta-percha it is gently pressed upon the coin and not removed till quite cold. The negative impression is then brushed over with the finest powdered plumbago (graphite), having been previously (if plaster of Paris) soaked in melted wax or paraffine. The wire being firmly wrapped round as before, the back is varnished and the metal deposited as previously described.

210. It will be understood how copper-plate engravings can be multiplied by galvano-plastic. The engraving must be covered electrically with copper, and this again covered with copper to reproduce the original, or the first impression may be made in plaster of Paris or soft gutta-percha. Wood engravings lose somewhat of their beauty on reproduction. Daguerreotypes may receive electrically deposited copper. In a daguerreotype the darkest portions are the deepest beneath the surface. Although the difference of elevation of the parts is almost microscopic, the copper faithfully follows the surface; the deepest parts of the daguerreotype are represented by the highest elevations of the copper impression: these take the ink and produce darkness in the print.

211. Without entering further into the technicalities of this beautiful art, there are still one or two points which may be mentioned. When the article to be coated is small, and time is no object, the battery is sometimes dispensed with; the object to be covered is then itself made to perform the function of the electro-metal of the battery. An arrangement of this kind is shown in fig. 156. A glass vessel A, containing sulphate of copper, is provided with a porous trough round its upper rim, as in Daniell's cell, for the purpose of holding crystals of sulphate of copper; or bags of that substance are hung round the edge. In this cylinder is a porous one C; or a glass one with a bottom made of bladder. C is filled with dilute sulphuric acid, and contains the zinc cylinder Zn connected by a wire with a tray B in the copper solution, upon which is placed the object to be coppered. The action needs no further explanation since it is precisely the action which takes place in a Daniell's cell, with the exception that in the latter the vessel containing the copper solution is itself wholly made of copper, whereas here the copper is only deposited on the conducting surfaces resting on B.

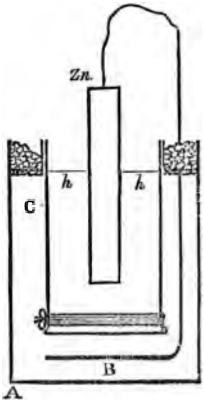


Fig. 156.

212. Glyphography may be briefly defined as the reverse of etching. A metallic surface is covered with wax, which is then scratched off where shadows or outlines are to appear. When the metal is soldered on to a wire, and, its back being covered, it is made the kathode in sulphate of copper or tartrate of iron and potassium, the metal is deposited on the exposed surface, and not on that wax-protected. On washing the wax off with turpentine and alcohol, an embossed engraving, or rather relief resembling a wood-cut, is obtained. The parts of the plate exposed are raised: they take the ink and produce lines or shadows in the impression.

CHAPTER IV.

MEASUREMENT.

213. We are now sufficiently familiar with what may be called the origin and general nature of the galvanic current to study its measurement. It must be borne in mind that the science is comparatively so new, and its phenomena so unfamiliar, that its nomenclature is largely borrowed from those of other branches of science. Analogies between different classes of facts are both useful and perilous. They are useful, indeed invaluable, in aiding the mind to get a conception of the unfamiliar, by referring it to the familiar: perilous because it is rare that any two physical analogies are perfect, and because if, as we are naturally inclined to do, we seek to trace analogies too far, and apply the adjectives of one branch of physics without reserve to another, we get soon bewildered by inconsequent conclusions.

214. **Water Currents through Tubes.**—If we accept the notion that when the poles of a cell or battery are joined, the whole circuit is traversed by a current of what is called Voltaic electricity, we may at once examine how far the analogies are preserved between this current and those with which we are most familiar, namely, the currents of air and water. Let us consider the flow of water along a horizontal cylindrical tube A filled with fragments of sponge or other substances which obstruct the flow. Let one end of A be in connection with a limitless reservoir of water, or one in which the surface of the water is always kept at the same height above the end of the tube, whatever be the quantity of water which flows through the latter. Let the sides of the tube itself offer no resistance to the flow. Let H be the height of the surface of the water above the end of A. Let the length of A be l, and its sectional area a. Let W be the

quantity of water which flows through A in the time t when A is empty. Let W' be the quantity flowing in the same time when A is full of sponge. Then $W - W'$ represents the deficit in quantity produced by the sponge, that is, the resistance of the sponge which we may call R', then $R' = W - W'$. When the height increases, the quantity flowing through in a given time, or current quantity, increases in the same proportion, so that for 2H we get $2W'$. We should also get 2W for 2H if A were empty, so that $2W - 2W'$ or $2(W - W')$ or 2R is the resistance when the height (or pressure) is 2H, and so on. Now it is clear, and also appears from experiment, that n tubes exactly like A, put side by side, will deliver (H being the same) just n times as much water as any one of them. In other words, a single tube of sectional area na will deliver n times as much water as a single tube of sectional area a, whether all be full of sponge or all empty. The total deficit which measures the resistance will be $n(W - W')$ or nR'. Again, if n tubes of length e each be placed end to end, they will, when empty and non-resisting, deliver for like pressure H the same quantity as one alone. But if, as before, full of sponge, the deficit, or measure of resistance will be $W - nW'$ or $Rn = W - nW'$. Resistance is here measured by deficit in resultant quantity.

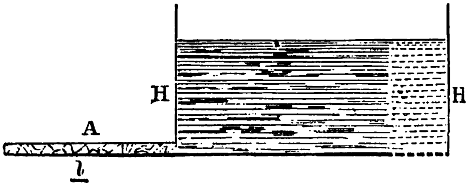


Fig. 157.

215. Next, fig. 158 (1), let two tubes A and B, of which B has twice the sectional area of A, be full of water and similiar resisting substance, and let them be connected at their ends by two enlargements which transmit the liquid pressure without obstruction. Let there be a pressure in B in the direction of the arrow of one gram per millimeter of sectional surface. There will be a pressure of one gram on *every square* millimeter of A. There will be half the total pressure on the A section that there is on the B section. The same quantity of water will pass through any complete section of A or B in the same time. Hence we have the following relations.

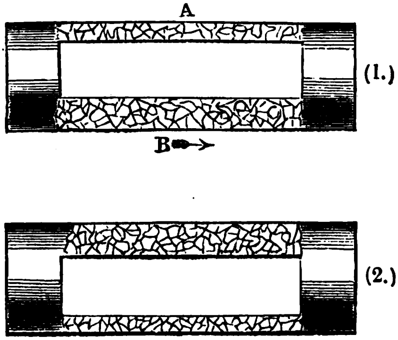


Fig. 158.

Quantity through A section = quantity through B section in same time.
Tension or pressure per square unit on A section = tension or pressure per square unit on B section.
Total pressure on A section = half total pressure on B section.
Rate of current through A section = twice rate of current through B section.

Precisely similiar relations would exist according to the well-known laws of hydrodynamics if, as in fig. 158 (2), B has half the sectional area of A.

216. Let us compare the above with the circulation of a Voltaic current in a single cell circuit. That which corresponds to the cause of the aqueous circulation (the pressure due to the height H, Art. 214, or the pressure in B, Art. 215), in other words, that which corresponds to the fluid tension is here called electromotive force. We need not consider now where it takes its origin. We know, fig. 159, that the current passes in the direction of the arrows, and that it meets with resistance both to its passage through the liquid, and its passage

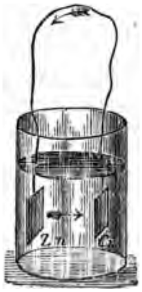


Fig. 159.

through the connecting wire. We know that the quantity of current passing through any complete section of the circuit in the same time is the same. This quantity measures the current strength. And here it must be well noted that we have a breach in the analogy in our nomenclature. For the current strength of a liquid stream, such as a river, is usually considered not as proportional to the quantity of water flowing down the whole channel in a given time, but to depend directly on that flowing through a unit of area, and is so used to express the same condition as velocity. The current quantity of an electric current is strictly analogous with the "volume" of water which the river pours down. The intensity of the electric current corresponds to the velocity of the liquid one.

217. Ohm's Law.—Let us by q denote the quantity of electricity which passes in a given time through any complete section of the circuit of fig. 159. Or, since we may always consider the time the same, let q denote the current strength. Let e denote the electromotive force of the cell. This depends wholly upon the nature and not upon the quantity of the constituents of the cell (just as the aquemotive force depends upon the height, and not upon the mass of water in the reservoir). Let the total resistance throughout the circuit be called r, and let electrical resistance be *defined* as that which, when doubled, halves the current strength, when halved doubles it and so on. We have then for a single cell—

$$q=\frac{e}{r}$$

The resistance r consists of two distinct parts, namely, the resistance in the fluid, which we may call f_r, and the resistance in the connector, which we may call c_r: then

$$r=f_r+c_r \ldots\ldots\ldots\ldots\ldots (\alpha)$$

and therefore

$$q=\frac{e}{f_r+c_r} \ldots\ldots\ldots\ldots\ldots (\beta)$$

Suppose now a number n of perfectly equal and similar cells are joined together, as in fig. 160 (1), to form a battery (in the fig. $n=3$). And let the terminals be joined together *by the same* wire which joined the elements of the single cell. And suppose the connections between the cells offer a negligibly small resistance. We have then, the electromotive force in each cell being the same, a total electromotive force of ne. Also the total fluid resistance must be nf_r, while c_r remains constant. Accordingly, if Q be the total current strength—

$$Q = \frac{ne}{nf_r + c_r} \ldots\ldots\ldots\ldots\ldots (\gamma)$$

Compare fig. 160 (1) with 160 (2). The two figures are lettered homologously. The electromotive force which we may suppose is exercised at the given surface *a* (1) is represented by the pressure *a* (2). The cell resistances or fluid resistances in (1) are represented by the tube resistances at *a*. The intermediate resistances *bb* in (1), which we suppose to be very small, are represented by the enlargements β,β in (2).

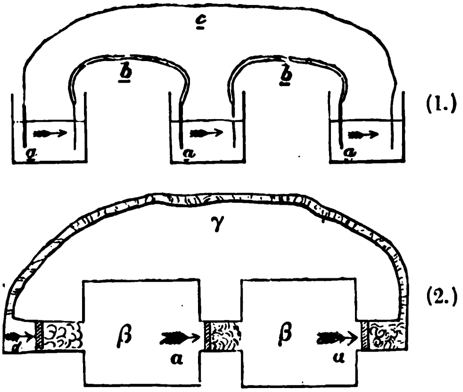


Fig. 160.

In the above battery arrangement two extreme cases may be considered, namely (1) when the connecting resistance is incomparably smaller than the fluid or cell resistance, and (2) when the fluid or cell resistance is incomparably smaller than the connecting resistance.

In the first case,

$$c_r = o, \text{ or } r = f_r, \text{ or } q = \frac{e}{r}.$$

and from (γ)

$$Q' = \frac{ne}{nf_r} = \frac{e}{r}, \text{ and accordingly } Q' = q$$

In the second case,

$$f_r = o, \text{ or } r = c_r, \text{ or } q = \frac{e}{r}$$

and from (γ)

$$Q'' = \frac{ne}{c_r} = n\frac{e}{r} \text{ and accordingly } Q'' = nq.$$

It therefore appears that when the connecting resistance is very small compared with the cell resistance, there is but little advantage in multiplying the number of cells when they are arranged as in fig. 160. But that when the cell resistance is very small compared with the connecting resistance, the quantity of electricity which passes is almost in direct proportion to the number of cells when so arranged. Hence, in order to overcome a great external resistance, that is, a resistance in the connecting circuit, the cells should be connected as in fig. 160, that is, zinc to copper alternately. Such an arrangement is called on arrangement for intensity.

218. Next let us take the elementary cell of Art. 217, and, instead of multiplying it, let us increase the size of its plates, retaining everything else as before. The electromotive force remains the same as before, for though there are *n* times as many regions where the electromotive forces act side by side, they no more assist one another than do the neighbouring vertical columns of water in a reservoir in affecting the pressure on the exit pipe. The external resistance, we will suppose, to remain the same. The increase in the size of the plates *must be* followed by a proportional diminution in their resist-

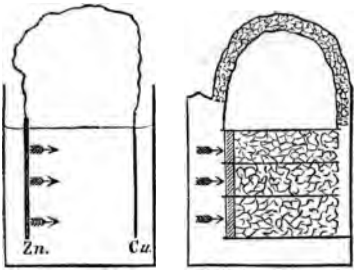


Fig. 161.

ance, or rather in a proportional increase in the quantity of electricity they allow to pass through. Hence

$$Q=\frac{e}{\frac{f_r}{n}+c_r}$$
$$=\frac{ne}{f_r+nc_r}$$

As before, let us see the effect of increasing the plate size (1), when the external resistance is incomparably smaller than the internal; and (2), when the reverse is the case. In the first case $r=f_r$ and $q=\frac{e}{r}$, so that putting Q_1 for the total quantity of electricity

$$Q_1=n\frac{e}{f_r}$$
$$=nq\ldots\ldots\ldots\ldots\ldots(5)$$

In the second case $r=e_r$ so that if Q_2 be the total current strength

$$Q_2=\frac{ne}{nc_r}$$
$$=\frac{e}{r}$$
$$=q$$

In other words, when the external resistance is very small, the making the plates n times as big sends nearly n times the quantity of electricity through the circuit. On the other hand, scarcely any advantage is derived by increasing the size of the plates if the external resistance is comparatively very much the greatest.

219. The effect of enlarging the plates may be obtained by connecting the plates of the cells of a battery in such a manner that all the zincs are connected together, and all the coppers (platinums or carbons) are together. The circuit is completed by joining the family of zincs with the family of carbons. Thus, in fig. 162, the cells are shown connected in the usual way. In fig. 163, they are connected in the second manner; and in fig. 164, three cells, forming a group, are connected in the first manner, while the groups themselves are connected in the second manner.

If the ratio between the total external resistance to be overcome and the resistance of one cell is known, the maximum current is obtained from a number of cells by so arranging them in groups that the number in each group is as near as possible a mean proportional between the total number of cells and the ratio between the resistance of one cell and the external resistance. And the maximum current is obtained, if the external resistance is fixed, by so arranging the cells in groups that the total cell resistance is equal to the connecting resistance.

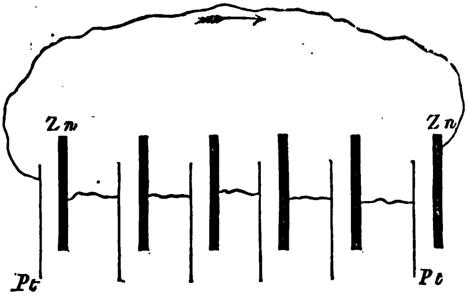


Fig. 162.

To prove these assertions let us call the arrangement, such as in fig. 162, tandem, and the arrangement of fig. 163 abreast.

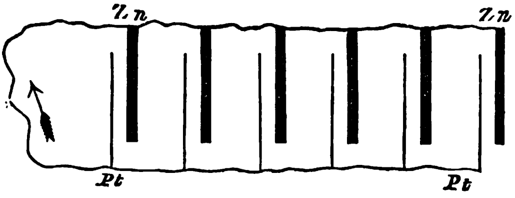


Fig. 163.

If we take a battery of n cells, arranged tandem, and take away half of the cells, we halve the electromotive force (which, in tandem, is additive), and we also halve the internal or cell resistance. Place now the two tandem halves of $\frac{n}{2}$ cells each abreast of one another, and connect the zinc pole of one with the zinc pole of the other, and likewise the two platinum poles together (fig. 164). The electromotive force is now the same as in the half battery; but the internal resistance is halved, because the size of each plate is virtually doubled by being connected with an equal plate. Accordingly, on breaking a tandem battery in half, and connecting the halves abreast, the cell resistance is made $\frac{1}{4}$ of that of the entire battery ranged tandem. If it be broken up into four quarters, which are arranged abreast, the internal resistance is $\frac{1}{16}$ of the original, and so on. In general terms, if it be broken up into (n) equal parts, the internal resistance will be a $\frac{1}{n^2}$ of the tandem battery. Thus, the internal resistance of fig. 163 is 36 times that of fig. 164. Consider now a tandem combination. We know that $Q = \frac{E}{F_r + C_r}$, when E is the total electromotive force, F_r the total fluid or cell resistance, and C_r the connecting resistance. Let now the battery be broken into n equal parts, and the parts join abreast. The electromotive force becomes now $\frac{E}{n}$. The internal resistance becomes $\frac{F_r}{n^2}$, so that

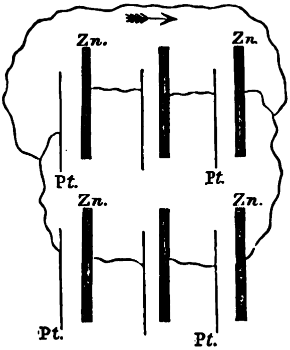


Fig. 164.

$$Q = \frac{\frac{E}{n}}{\frac{F_r}{n^2} + C_r}$$

$$= \frac{E}{\frac{F_r}{n} + nC_r},$$

If now $F_r = C_r$ this becomes $Q = \frac{E}{F_r\left(n + \frac{1}{n}\right)}$, and since $n + \frac{1}{n}$ must always be greater than 2, by making $F_r = C_r$ the denominator of this fraction becomes as small as possible, and consequently Q as great as possible.

Again, if we have N cells, with which we wish to send as strong a current as possible through an external resistance C_r, into how many tandem batteries shall we divide N? Let the most favourable arrangement be that in which there are n groups of m cells each. We wish to find m, and we know that $n\,m = N$. If f_r be the resistance of a single cell, the total internal resistance of the combination is $f_r\,\frac{m}{n}$. Since, however, we know that for the maximum current the internal must be equal to the external resistance, $C_r = f_r\frac{m}{n}$, but $n = \frac{N}{m}$, so that $C_r = f_r\frac{m^2}{N}$, and therefore $m = \frac{\sqrt{N\,C_r}}{\sqrt{f_r}}$. Or m is the mean proportional between the number of cells and the ratio between the external resistance and that of one cell.

219. The above laws, which are the only ones of Ohm's laws which we need consider, are of great use in the quantitative examination of current effects. The three most conspicuous ways in which the quantity of a current is measured are:—(1), Its mechanical power of turning a magnetic needle in opposition to the directive magnetism of the earth; (2), the chemical power of separating and rearranging the particles of liquid conductors; and (3), by the heat produced in conductors—both liquid ones, which undergo electrolysis, and solid ones, such as metals, which conduct without undergoing decomposition.

220. The Tangent Galvanometer.—Already, in Art. 141, we have seen how a current, passing in the same vertical plane as a magnetic needle, and either above or below it, will deflect the needle out of its magnetic meridian, and retain it in its displaced position. We shall examine in the sequel the precise relation of such displacement in numerous cases; but here we may assume that a current passing from S. to N. above a magnetic needle turns the N. end of the needle to the E. Also, if a current passes from N. to S. below the needle, the N. end will also turn to the E. In other words, if a *current circulates* around a needle in the place of the magnetic meridian, the needle will turn out of the magnetic meridian and take up a position depending (1) upon the strength of the circulating current; (2) its distance from the needle; (3) the earth's magnetism. A magnetic needle which is displaced seeks to regain its former position—one end is pulled towards the N. and the other towards the S. pole of the earth. These forces act with the greatest leverage upon the needle when it is at right angles to them; that is, when it is forced into a position E. and W

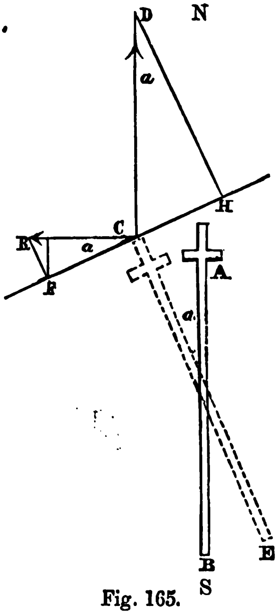


Fig. 165.

On the other hand, forces acting E. or W., to turn the needle out of the magnetic meridian will act most effectively when at right angles to the needle, and less and less advantageously as the needle becomes more and more displaced. By measuring the angular displacement which the needle undergoes when a current passes round it in the magnetic meridian, the ratio between the directive magnetism of the earth and the repellant action of the current is at once obtainable. Thus, let a current S N pass above the magnetic needle BA, both being in the magnetic meridian. Let the needle be thereby deflected through an angle a, and take up a position EC. We need only consider the forces on the end C of the needle: for all the others on the same half of the needle are similar, and those on the other half symmetrical. Since C is at rest, and is acted on only by the directive force of the earth in the direction CD, and the repellant force of the current in the direction CR, it follows that the resolved parts of these forces at right angles to CE are equal and opposite. Make, therefore, CH and CF equal to one another (of any arbitrary length), and draw FR and HD at right angles to

FH. Then CD and CR will relatively have the respective magnitudes of the directive magnetism of the earth and the repulsion of the current. It is clear that the angles CDH and RCF are each equal to α.

$$
\begin{aligned}
CF &= CR \cos. \alpha. \\
CH &= CD \sin. \alpha. \\
CF &= CH \\
\therefore CR \cos. \alpha &= CD \sin \alpha. \\
CR &= CD \tan. \alpha.
\end{aligned}
$$

Or the repellant action of the current is equal to the directive force of the earth, multiplied by the tangent of the angle of displacement. If, while the earth's magnetism remains the same, a second current gives a deflection β, it is clear that we should get

$$\frac{CR}{CR'} = \frac{\tan. \alpha.}{\tan. \beta.}$$

Or this ratio of the repellant effects of the current is proportional to the tangents of the angles of deflection. Hence the instrument is called a tangent galvanometer. If the needle be very small, the repellant action of the current is directly proportional to the current's strength; so that the latter is measured directly by the tangents of the angular displacement.

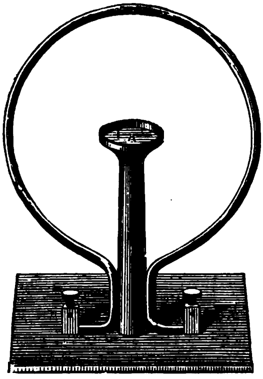


Fig. 166.

The strength of the magnetism of the needle is without influence upon the indication; for while a strongly magnetized needle is more strongly repelled by the current, it is also more strongly directed by the earth.

If the needle is of a considerable size in respect to the ring around which the current passes, the ends of the needle will become sensibly further from the current after deflection, and too low a reading will result. If the needle be placed on one side of the ring at a considerable distance away, the reading is again faulty, but by excess. For, as the needle turns, one end approaches, and the other recedes from the ring; and the effect of change of distance on the nearer end is greater than on the more distant. It has been shown that when the needle is placed from the centre of the ring, at a distance equal to one quarter of the ring's diameter, these errors eliminate one another. If the current is made to pass in succession in opposite directions around two such rings, the most favourable conditions obtain, and the most exact measurements got.

Fig. 167 shows the single ring Tangent Galvanometer or Rheometer, which can be understood without further explanation.

221. The Sine Galvanometer.—Imagine the current to have produced a certain deflection in the tangent galvanometer. Let now the ring which conveys the current be turned on a vertical axis in such a manner as to pursue the needle. The needle retreats further and further, but more and more reluctantly, because the earth's magnetism acts more and more perpendicularly to it. At last the ring and needle are forced into one plane. The repellant force of the current acts at right angles to the needle, while as before, fig. 165, the resolved part of the earth's directive force at right angles to the needle is proportional to the sine of the angle of displacement. And these forces at right angles to the needle being equal to one another, it follows that the current repulsion is equal to the earth's directive magnetism, multiplied by the sine of this angle of displacement, which is the angle through which the wire has been turned. Or the strengths of two currents are to one another as the sines of the angles through which this ring must be turned to overtake the needle.

222. Absolute Galvanometer. — Still another form of galvanometer is shown in fig. 167, its principle depends upon the measurement of the current strength, by finding what torsion force is necessary to bring to a given distance of one another electro-magnets which are so excited by the passage round them of the current that they repel one another. The principles involved are: (1), that the torsion of an elastic wire is directly proportional to the angle of torsion; (2), that within certain limits the magnetic power of an electro-magnet (see Art. 229) is proportional to the square of the current strength. The current enters at *a* by the screw clamp, thence it passes beneath the circular wooden stand *c*, along the copper wire *a b*. It rises vertically and coils round a soft iron mass *f*, which lies horizontal and tangental to the axis of the instrument. It passes down and across the centre of the board, then rises and coils round a soft iron mass *f*, exactly similar and similarly placed to *f*, but on the opposite side of the instrument. Having encircled *f'*, the current-bearing wire again descends, and carries a mercury cup *g*, through whose bottom it passes, and which is exactly in the axis of the instrument. The current then leaves the mercury by the wire *i* which dips into it. It then traverses the wire round the iron *m*. Thence it crosses the instrument and forms a spiral round *m'*, after which it passes into the mercury cup *h*, which is exactly below *g*, and so to the binding screw *e*. The spirals are such that there is repulsion between *f* and *m*, and also between *f'* and *m'*. It is seen that the magnetic pair *f f* is fixed. The pair *m m'* is movable about a vertical axis. The system *m m'* is hung by a metal or glass thread *k* from the rod *l*, which works stiffly through the nut *o*. The latter carries an arm and vernier *p*, which slides upon the graduated head *q*. The scale, nut, etc., are supported on the glass tube *r*, which is fastened by the cross *s* on to the plate-glass disc *t*, which rests upon the top of the glass cylinder *v*, clamped upon the wooden base *e*, resting on levelling screws. In the side of *u* is a flat glass window *w*, through which a vertical line of light may be focussed upon *x*, a mirror fastened vertically

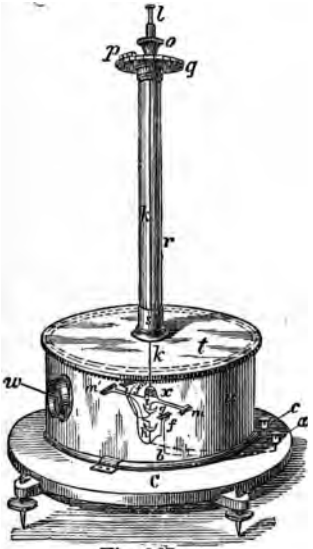


Fig. 167.

to the *m m′* system; and thence thrown upon a scale in the manner now so often employed.

When the instrument is used, the upper plate *t* and the system *m m′* are removed by lifting *v*. The edge of *u* is rubbed with bees'-wax to prevent *t* from slipping upon it. The copper wires penetrating the cups, and those which are to touch the mercury above are amalgamated, and a little mercury is poured into the cups. Thin amalgamated platinum foil is then pressed into the cups, and mercury is poured upon it. By this means the meniscus is concave, and the hung wires tend towards the centre of the cups. The upper part is then replaced, and so adjusted by turning the plate *t* and the cylinder *u* that the mirror *x* is parallel to the window *w*, when the axis of *m m′* makes an angle of about 15° with that of *ff′*. The rod *l* is adjusted so that the wires of *m m′* just touch the mercury; and by the levelling screws *k* is so swung that *m* and *f*, and also *m′* and *f′* are exactly opposite to one another, and the wires in the centre of the mercury cups. A slit of light is then sent through *w*, reflected by *x* on to a screen, and the head *o* is so turned that the slit is split by an arbitrary vertical line on the screen. The reading of *p* is then noted. A current passing through the system forces *m m′* away from *ff′*. Turn the head *o* until the slit of light is again brought to the mark on the screen. The angle through which it must be turned is directly proportional to the magneto-repulsion at that distance. Another current necessitates a different amount of torsion to bring the light to the same spot, that is, to bring the electro-magnets to the same distance as before. The two readings of torsion are proportional to the squares of the currents which produce the repulsions. The device of bringing the repellant magnets to the same distance from one another, gets rid of a whole series of sources of error. Many of the laws of electro-dynamics may be readily illustrated by this instrument, and not only may the strengths of different currents be directly compared, but also the absolute magneto-mechanical value of the current may be determined, if we know the torsion strength of the wire.

223. Voltameter.—That form of galvanometer or rheometer which depends upon the measurement of the amount of chemical change effected by the electrolytic action of the current, is usually called a Voltameter. In Art. 181 we have seen how the current from a battery, passing by means of platinum electrodes through acidulated water, resolves that liquid into its elements. The liquid which suffers electrolysis offers resistance, so that when we find a certain amount of electrolysis produced in a cell of water interposed in a circuit, through which a current of given strength is passing, we must not look upon the amount of electrolytic products as a measure of the current strength which was at first passing, but of that which is now passing. But if we interpose a tangent galvanometer, or absolute galvanometer in the circuit as well as the electrolytic liquid, we shall find that the amount of chemical work done, that is, the amount of decomposition effected, is directly proportional to the current strength as measured by one or other of these galvanometers. Fig. 168 shows the usual form of the Voltameter. A glass tube *a*, graduated into cubic centimeters, fits into one neck of a Woullf's bottle *b*. Through the lower end of *a* are fused through the glass two platinum wires *c d*, which carry two vertical platinum foils placed as close together as convenient. The bottle *b* is filled completely with dilute sulphuric acid. The tube *a*, being also so filled, is inverted into the one neck of *b*. As much acid is then poured out of the other neck of *b* as is about equal to the contents of *a*. On introducing *e* and *d* into the circuit, the mixture of hydrogen and oxygen collects in *a*, and, making proper correction for temperature and pressure, may be there measured. In order to establish the law that a current of twice the strength as indicated by the galvanometer always gives twice the amount of electrolytic products, and so on, it is necessary

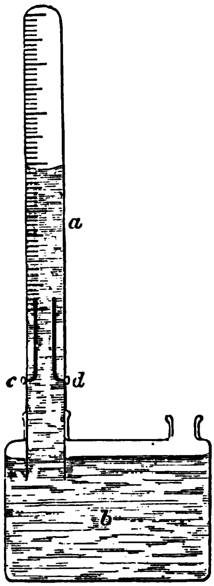


Fig. 168.

to introduce into the circuit some means for bringing the current to a certain strength after the introduction of the electrolytic Voltameter. One method of doing this is by employing a rheostat or rheochord, which will therefore be described immediately.

224. The **Rheostat** has its name from the possibility, by its use, of reducing the strength of a current till it becomes of a certain predetermined strength. This it effects by introducing into the circuit a resistance which can be increased or diminished at pleasure. For the present we will only assume that the resistance in a wire increases with the length of the wire. So that if we introduce a certain length of wire into a circuit, we diminish the current strength more than if we introduced a shorter wire of the same material and thickness. Let E and B be two perfectly equal cylinders which can turn on horizontal axes parallel to one another. The cylinder E is made up of glass or other non-conducting substance. The cylinder B is made of brass. A German silver wire having its end attached to the axis of E is wound round that cylinder in a fine spiral groove, the other half of which is wound round the cylinder B in the opposite direction, and is attached to the axis of B. It is clear that the resistance which the current experiences in the rheostat is that due to the resistance of as much of the German silver wire as is coiled upon the non-conducting cylinder E, and bridges over between the two cylinders. For on reaching the cylinder B the current meets with such a large mass of conducting material as to allow it to pass without obstruction. On turning E round in a left-handed direction, some more of the thin wire will be rolled on to E, and through this additional length the current will have to pass, and will therefore encounter a greater resistance. On turning B in the same direction, an opposite result must ensue.

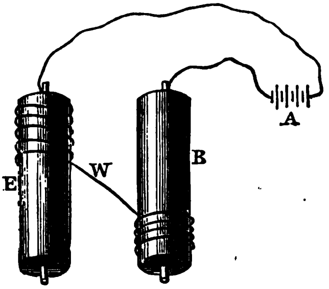


Fig. 169.

The current can therefore be weakened at pleasure, up to the amount attainable by the introduction of the whole of the wire.

Returning now to Art. 222, let this rheostat, a Voltameter, and a galvanometer, be all introduced into the circuit from a battery of say two cells of Grove's. Let the cylinder of the rheostat be so turned that the needle of the tangent galvanometer points to 45°; and suppose that we watch the needle, and when it shows any sign of returning, we diminish the resistance of the rheostat, and so favour the strengthening of the current, and so keep the needle for five minutes at 45°. Imagine that in this time 20^{cc} of mixed gas are collected. If we then so adjust the rheostat, that for five minutes the tangent galvanometer indicates 63° 30′, we know that twice the current quantity has passed, because $\tan. 45° = 1$ and $\tan. 63° 30' = 2$ nearly. Accordingly, we find that in the second five minutes 40^{cc} of gas have been evolved.

225. The Rheocord is a form of instrument for use where, owing to the strength of the current, the rheostat, by reason of the necessary thinness of its wire, cannot advantageously be used. Suppose the German silver wire ABC, fig. 170, to be doubled at its middle B, and to be stretched horizontally in two parallel lines between two uprights E and F fastened to a board. Let the wire pass tightly through two holes in the top of an iron thimble G, and also through two holes in a cork in the neck of the thimble. The thimble is filled with mercury, and may be slided upon the wires. If it be brought near to E, the current which enters A will traverse only a short length of wire before it meets the thimble and mercury.

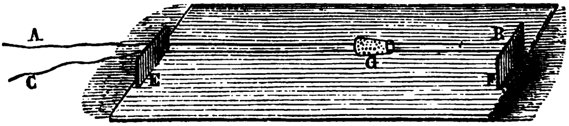


Fig. 170.

It will then take the short cut through the mercury to get back to C. The distance of wire to be traversed will be greater according as the thimble approaches B. One can use such a rheocord in place of the rheostat, in the experiment of Art. 224, to maintain a current of constant strength as measured by an interposed galvanometer.

226. The Voltastat and Voltameter.—It is possible to make the current to a certain extent interpose, by its own greater or less action, a greater or less resistance in its own circuit, and thus perform upon itself an action somewhat similar to that effected by the governor of a steam engine. This is effected in the Voltastat or automatic rheostat, an instrument which can likewise be used as a Voltameter. A wide glass tube T, open at both ends, passes air tight through the cork C of the glass cylindrical vessel G. Two platinum wires *p*, *p′* fused into glass also pass through the cork, and are attached below to two triangular sheets of platinum foil which have their apices downwards, and are inclined outwards from the axis of the glass. Through the cork also passes a tube D. This is open at the bottom, but at the outer extremity it is fused so as to leave an exceedingly fine capillary opening. The whole is filled with dilute sulphuric acid, so that the platinum plates are just covered. The relative capacities of the tube T, and the cylinder glass, are such that the capacity of T, from the level of the liquid in G to the top of T, is about equal to the capacity of the cylinder G from the level of the liquid to the bottom of the platinum plates. On sending a current from *p* to *p′* between the platinum poles, the electrolytic gas accumulates above the surface of the liquid, and while some of it escapes through the capillary opening in D, this being insufficient, the liquid is forced up the tube T, whereby the upper, wider, and nearer parts of the platinum poles are laid

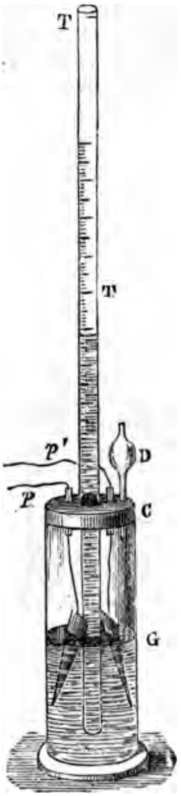


Fig. 171.

bare. The resistance between the poles is thereby increased, the current is diminished in strength, and less electrolytic gas being formed, the opening at D is able to relieve it. In a short time a condition of equilibrium is established, the water in T being of such a height that its pressure is exactly capable of forcing out sufficient gas through D to keep a definite fraction of the poles in action. Further, if by actual measurement we know how many cubic-centimeters of the gas are delivered through D per minute, when the liquid in T stands at a certain height, we will know that we have a current of that electrolytic power whenever the liquid stands at that height in T. The tube T may be thus graduated and calibrated, and the strength of the current thus at once determined, the measurement being of course accompanied by a diminution of the current's strength below that which it would have without the intervention of the Voltastat.

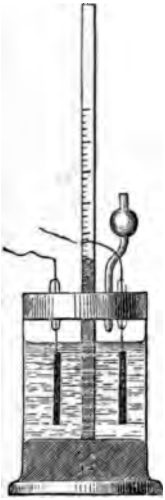


Fig. 172.

When used as a Voltameter simply, the instrument may advantageously have the form of fig. 172; the platinum poles are then rectangular, and remain totally immersed throughout. To this end the manometer tube T should be much thinner, and may be advantageously made to dip into mercury at the bottom of the acid. This enables T to be much shorter.

CHAPTER V.

ELECTRO-MAGNETISM.

227. Already in Art. 142, and in speaking of the galvanometer in Arts. 220, *et seq.*, we have seen that a current passing above from S. to N., and at right angles to a piece of steel wire lying E. and W., so magnetizes the wire that its west end will afterwards point to the N., just as though a + spark had passed above it in the same direction. If we replace the steel wire by a bar of soft iron, the other conditions being as before, the iron will become a magnet as long as the current is passing. A second current by the side of the first will produce an identical effect, and strengthen the magnetism produced by the first, and so on. A current passing in the opposite direction, that is, from N. to S. below the needle, will also confirm the magnetization effected by the first current. Thus in fig. 173 (1), the current passes upwards and in front of the bar; the bar becomes so magnetized that the end to the left repels the marked or N.-seeking end of a magnetic needle, and therefore itself has N.-seeking magnetism. In (2) the same polarity is produced by a current which descends behind the iron bar. In (3) we have four upward currents in front, and four descending behind. The induced magnetism is the same as before, only stronger. In order to remember which end of the bar becomes N.-seeking, you may suppose yourself to be in the current which enters your feet and leaves your head. Place yourself so as to look at the bar of iron. That end of the bar will become N.-seeking which is on your left hand. Instead of employing separate currents, let the ends of the wires be joined as in (4), so that one and the same current encircles the rod in a spiral. The same polarity is produced, for the same end of the rod is on your right hand continually as you swim in the current and with the current, and keep your face to the rod; and this not only when you pass up and down, but also as you continually are turning head over heels around the rod. The spiral formed in this way is shown more clearly in fig. 174 (1). If, on the other hand, we suppose the currents to descend in front of the bar, and to ascend behind it, and to be joined as before to one spiral current, then fig. 174 (2) as we swim as before in and with the current and regard the bar, the N. being on our left hand will be on the right of the figure. The current, passing from left to right in both figures, passes (fig. 174) along a left-handed spiral or helix in fig. (1), a right-handed spiral in fig. (2), and opposite *polarity is the consequence.* The right-handed spiral is far

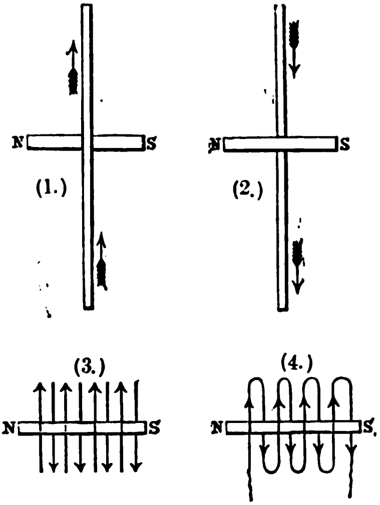


Fig. 173.

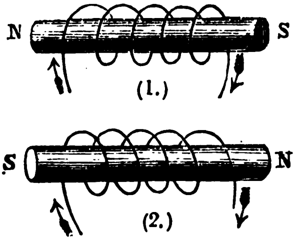


Fig. 174.

more common in the arts than the left-handed spiral. Screws for wood or for cork have to thrust forward as they are turned round. Using, as most of us do, our right hand for this purpose, we get a greater leverage upon the handle of the tool if we turn our hand in the direction of the motion of the watch hands, for we have our hand then applied at two parts as wide apart as possible, namely, the inner edge of the thumb, and the outer edge of the palm near the little finger. If we try to turn the tool in the opposite direction, we can only grasp it between the edge of the thumb and the neighbouring edge of the fore finger, which, being nearly opposite to one another, give little moment to the couple. Hence it is that screws, spirals, or helices are called right-handed when they are like that of fig. 175 (*a*), left-handed when like that of fig. 175 (*b*). It is easy to draw a right-handed screw or helix by making a heavy down stroke from right to left, concave side upwards. If we commence by making a heavy down stroke, concave side upwards from left to right, we naturally fall into the fashioning of a left-handed spiral.

The magnetic polarity induced in the soft iron may be summed up as follows. If a current passes around a bar of soft iron in a right-handed helix, the end of the iron where the spiral quits it becomes N.-seeking.

It is seen that left and right-handedness of spirals are essential qualities, that is, the one is not changed into the other by turning round. They are symmetrical, not similar. They are like left and right-handed gloves. The glove of the left hand will not fit the right hand unless turned inside out. So a right or left-handed spiral becomes left or right-handed respectively, when turned inside out.

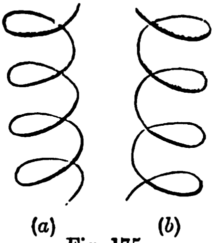


Fig. 175.

228. Further, remembering the rule of polarity in Art. 227, it appears that if a current passing down a right-handed spiral from left to right makes the right end of the rod N.-seeking; if it pass down the same spiral from right to left, it makes the left end N.-seeking. Again, if we wrap a wire round a cylinder in a right-handed spiral, from the end A to the end B, and keeping the winding continuous we bring it back from B to A (as on a reel of cotton), the return spiral is left-handed. Since now the current passing from end A to end B along a right-handed helix makes B N.-seeking, and in passing from B to A down a left-handed spiral, it makes B N.-seeking again, the two parts of the current assist one another in magnetizing the iron with identical polarity. So that if the iron be turned round on its axis, always in the same direction, the wire may be spun on it from end to end and back, or heaped in manifolds at any places; the effect is cumulative, provided that the wire is not allowed to be in metallic contact with itself or with the iron. If only one helix is to be used the wire may be naked, but the iron must be covered with some non-conducting material such as cloth. If many folds of the wire are to be applied, the wire itself is spun over with cotton, which is then varnished with shell-lac varnish. Wire covered with gutta-percha or other insulating material, such as is used for the electric telegraph, serves perfectly for making electro-magnets. The coil of wire may, for many purposes, be advantageously wound upon a brass or ebonite cylinder, into which the soft iron core fits rather closely. If two such cores are placed parallel to one another, and fastened at their lower ends to a third cross-piece of iron, each core may be encircled by a coil, and the two terminals of each coil may be so connected with one another and with the wires from the battery, as either to cause like or unlike polarity at the free ends of the cores.

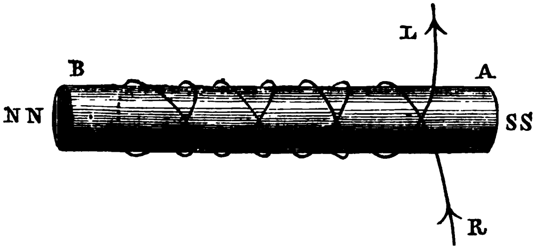


Fig. 176.

Thus, in fig. 177, if the terminals of the coil around E are *a* and *b*, and those around F are *c* and *d;* and if the platinum pole of the battery B is joined to *b* and the zinc end to *a*, the free end of E becomes S.-seeking. If *a* be joined to *c*, and *d* to Zn, the free end of F becomes also S.-seeking; but if *a* and *d* are joined, and also *c* and Zn, then the free end of F becomes N.-seeking. When arranged in the latter manner the electro-magnet exerts an attractive force far exceeding that of the most powerful permanent magnets. Many hundredweights are supported by an electro-magnet, weighing twenty or thirty pounds, and the phenomena of diamagnetism are easily shown. Electro-magnets are also advantageous for imparting permanent magnetism to steel bars. The bars are rubbed upon the magnetic poles, in the way which will be described in Book II., on Magnetization. It is remarkable that while soft iron is so easily temporarily magnetized by the current, and steel easily magnetized by contact with the so formed electro-magnet, the steel is difficultly and imperfectly magnetized when surrounded by the current alone.

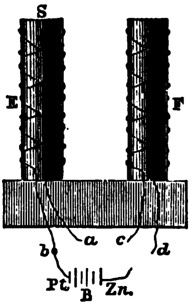


Fig. 177.

229. It is clear that the strength of the electro-magnet depends upon two variables, namely, the strength of the current, and the number of folds of the spiral. It is of little consequence whether the folds of the wire are close or separate (for the same number), provided the core somewhat protrudes. If the same coil is employed in the same position, and the current strength alone varies, it is found that the strength of the magnet (as measured by its attraction to soft iron), varies directly with the current strength, while the attraction between the unlike poles of two similar and similarly traversed electro-magnets varies with the square of the current strength. In like manner, if the current strength remain constant, the strength of the electro-magnet (its attraction to soft iron) varies directly with the number of folds of the helix; while the attraction between two electro-magnets varies with the square of such number. The magnetization of the iron core has, however, a limit, and the above laws are only strictly true when the currents are weak, with regard to the possible magnetization of the core; or when, by the fewness of the folds of the coil, the iron is far from magnetic saturation. As the saturation approaches completeness, the effect of equal increments to the current strength, or to the number of folds, fails to produce an equal increase of strength. Every iron bar has a condition of magnetic saturation, and the amount of this is proportional to the sectional area; that is, in a round bar to the square of the diameter. Experiment shows that if we wish to excite the same fraction of their maximum magnetism in two bars of unequal diameters, we must employ currents whose strengths are to one another as the square roots of the third powers of the diameters. Finally, if we use the same current (and spiral) to magnetize rods of different thicknesses, we find that the magnetism is proportional to the square root of the diameter.

230. Sustaining Power of Magnets.—The relation between the size and shape of the soft iron mass connecting the unlike poles with one another (which is called the keeper), and the force necessary to pull the keeper off when the electro-magnet is excited by a given current, is not accurately known. It appears that if we take a given electro-magnet, and employ heavier and heavier keepers, we can support heavier and heavier weights which are hung to the keeper; and that the maximum sustaining power is reached when the weight of the keeper is a little greater than that of the core of the electro-magnet. But although the mass of the keeper thus augments the sustaining power, the size of the surface of contact diminishes it. Thus, a keeper offering a circular surface of contact of half an inch diameter will carry twice as much as one with an inch diameter, if the magnet is tolerably strong.

231. Sound produced by Magnetization.—If a rod of soft iron be magnetized to saturation, it increases to the amount of about $\frac{1}{270,000}$ of its length. This increase in length is accompanied by such a decrease in thickness that the volume of the bar remains the same. This latter fact is proved by enclosing the iron bar A (fig. 178) in a glass tube B which is closed at one end, but drawn out into a capillary tube *c* and bent down at the other end. The end *c* dips into water which is made to stand at *c* in the capillary.

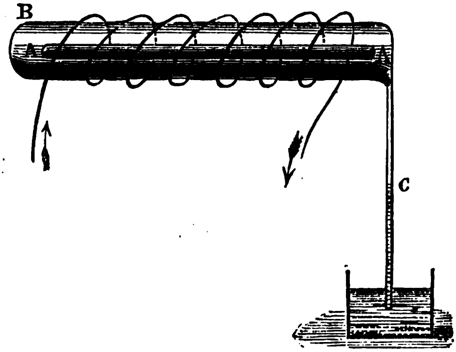


Fig. 178.

A spiral of wire is wrapped round B, and through this a current is passed. The slightest alteration in volume of A would be indicated by a rise or fall of the level of the water in *c*. This does not take place, and therefore the bar A does not change in volume. The magnetization of the bar is, however, accompanied by a sound like the tick of a watch, and if the bar be magnetized and demagnetized in rapid succession, a note is produced which may be rendered very distinct if the ends of the bar are rested between the bridges of a sounding box, as in fig. 179. Here the ends of the bar

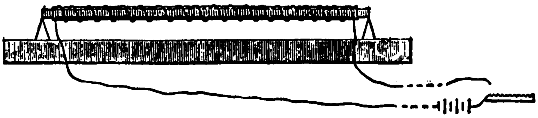


Fig. 179.

to be magnetized project beyond the glass tube upon which the wire is wound. The battery may be placed in a distant room to avoid the inevitable sound of the making and breaking of the contact with the battery. The rapid make and break may be effected by fastening one circuit wire permanently to one pole of the battery, and fastening a steel rasp to the other. The second connecting wire is then drawn along the rasp, and so alternately completes and breaks the circuit. The automatic make and break, to be described in Art. 235, may be used instead of the rasp. The purest tones, which are in fact the fundamental notes of the longitudinally vibrating bar, are produced when the bar is fastened only in the middle, and its two free halves surrounded by coils which do not reach one another in the middle. A steel wire, similarly encircled, when stretched so loosely that only the longitudinal note can be produced by friction, gives only this note when magnetized. If sufficiently stretched to give also its fundamental transverse note, the latter is also produced by the magnetization.

232. The fundamental longitudinal note may also be got from an iron rod, through which (instead of around which), the current is passing. An iron rod is clamped in the middle and there fastened to a sounding board. Its ends are armed with copper hooks which dip into mercury cups. These are connected by wires to the distant battery where the make and break occurs. For this effect the rod should be rather thin. A similar sound is produced in a hollow cylinder of sheet-iron when a coil is placed co-axially with it, inside it, and an interrupted current sent down the coil. The note is produced whether the cylinder be entire or divided down one side. If other metals than iron be used for the cylinder, no note is produced as long as the cylinder is quite closed or perfectly slit. But if the edges of a slit cylinder of zinc or other metal are in contact with one another, a noise results. Other metals than iron produce no tone when encircled or traversed by the current, with the exception of nickel and cobalt, and probably in a lesser degree the other magnetic metals.

233. The explanation of the above phenomena probably depends upon the attitude which the irregularly-shaped particles of iron endeavour to take, and partly succeed in *taking,* when in the neighbourhood of the current. We have seen how a piece of soft iron becomes magnetized when a current passes across it; we have also seen how a magnet tends to set itself at right angles to the neighbouring current. The current, in passing through the spiral of Art. 231, is always nearly at right angles to the axis of the iron rod. So that the irregularly-shaped particles of the iron will strive to set themselves with their longer axis parallel to the axis of the rod, their shorter axis transversely. As far as they succeed in doing this they will make the rod longer and thinner without altering its volume. In the case of the rod, through which the current passes, Art. 232, it is probable that the influence of the current is exerted to set the particles with their longer axes at right angles to the rod, and so to shorten it. If this view be true, the tone produced by the iron cylinder in which the spiral is placed should be accompanied by a lengthening of the cylinder. The cause of the noise of the split cylinder of non-magnetic metal is probably due to quite another cause, namely, the leaping across the imperfect connection where the edges are in contact of the induced current in the metal cylinder. See Chap. IX.

234. That the axial arrangement of the particles is the most probable cause of the elongation of the iron rod, encircled by the current, is proved by employing the particles of some magnetic substance in a medium in which they can easily move and arrange themselves. The magnetic or $\frac{3}{4}$ oxide of iron (Fe_3O_4), got by precipitating a mixture of a sesqui and a per salt of iron by ammonia, when shaken with water, arrests almost all light. Such a mixture is poured into a brass tube D, fig. 180 (1), the ends of the tube are closed by glass plates, and the tube itself is encircled by a

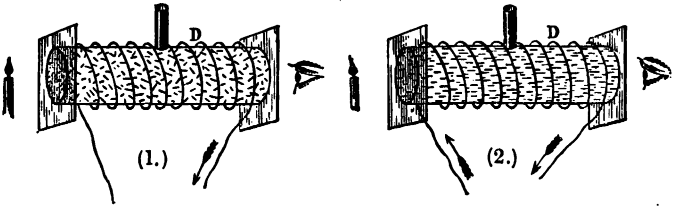


Fig. 180.

coil. A light placed before one end is scarcely visible at the other, because the particles of Fe_3O_4 are arranged promiscuously in the tube (1). But when the current circulates, the particles arrange themselves as on (2), which is shown by the light becoming distinctly visible.

235. Automatic Make and Break.—One of the contrivances of the greatest use, the action of which depends upon the development of electro-magnetism—is the automatic make and break. Fig. 181 shows the "hammer break."

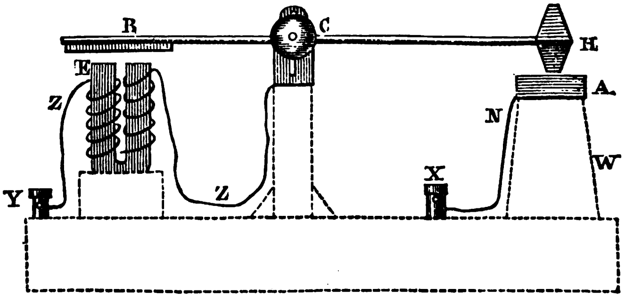


Fig. 181.

The dotted lines are the outlines of the wooden portions which serve as non-conducting supports. A hammer HCB rests its head upon the metal anvil A, which is connected by the wire N (fig. 181) with the binding screw X. The metallic shaft of the hammer turns on a pivot in the metal cap C. The end of the shaft or handle B is of soft iron, and is poised about $\frac{1}{8}$ in. above the poles of the possible electro-magnet E, when the hammer head is on the anvil. From Y, the second binding screw, a wire encircles the limbs of E in such a fashion as to make their ends N. and S. (when the current passes), and crosses over to C. The wires from the battery being fastened to Y and X, a current starts along Z, encircles E, crosses to C and so to H, thence to A and so through N to X. The circulation round E converts it into an electro-magnet, which instantly pulls B down and so lift H froms off A. The current is broken by this gap. The current ceasing, E is no longer magnetic, B ceases to be attracted, H falls upon A, the circuit is completed, B is again pulled down, and so on. By means of a screw, C may be raised and thereby B is raised, so that the action of the magnet upon B may be lessened. This adjustment is so made that B never actually touches the magnet.

236. If it be desired to get a still more nimble making and breaking of the circuit, instead of using gravity to restore contact, the elasticity of a steel spring is employed. Fig 182 shows the current entering at X and circulating around the soft iron E, and descending to the brass block G. In G is fastened a steel spring H which carries a little block of soft iron F, which is pressed to within about $\frac{1}{8}$ in. from the poles of the magnet by the point of the screw S, which works through the metal cap B, to which is fastened the wire leading to the other binding screw Y. The circuit is in the figure complete. But E being thereby magnetized, drags F away from B, and breaks the circuit at G.

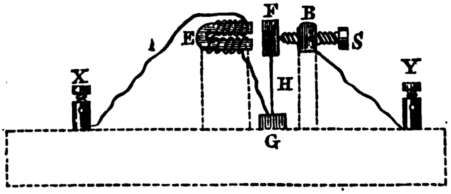


Fig. 182.

237. Electro-magnetic Machines.—The enormous power of attraction exercised by electro-magnets on soft iron, and on one another's opposite poles, when the distance between the attracting masses is small, and the perfect control which can be exercised over the establishment and direction of the current, soon suggested the employment of electro-magnetism as a motive power. This has been done chiefly in two ways: (1), by obtaining a reciprocating action similar to that of the piston of the steam engine; and (2), by getting at once a rotation by attracting successive parts on the circumference of a wheel, and so producing a motion similar to that of a water-wheel. The essential parts of the machine constructed on the first of these methods is shown in fig. 183. Two upright coils A and B enclose at their lower ends two soft iron cylindrical cores C and D. Similar bars E and F are fastened by jointed rods to the extremities of the lower G which turns around G. The arm of G is prolonged, and is jointed on to the crank of a fly-wheel. The axis of W bears an eccentric H which works the rod K backwards and forwards. K is armed with two or three blocks which work in a slot upon the bed L. This is of non-conducting material. The slabs are so adjusted that when the current passing round one coil has brought the movable core down to the fixed one, the eccentric just moves the slider along so as to break the contact through that circuit and establish it in the other. In fact, the motion is a close counterpart of that of the sliding valve of the steam engine.

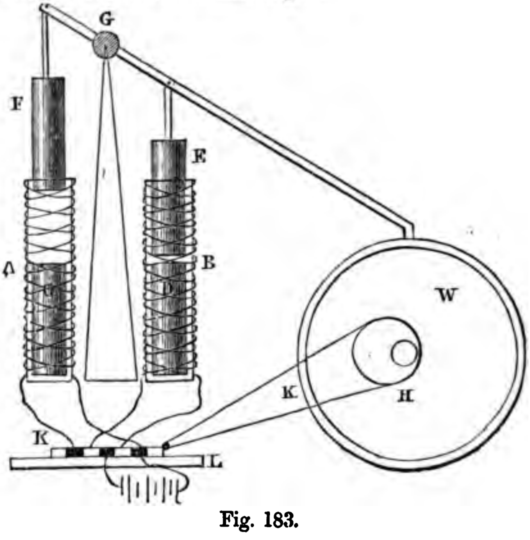


Fig. 183.

In the rotary engine, bars of soft iron are arranged around the circumference of a wheel, like the buckets of an overshot water-wheel. Electro-magnets are fixed around the circumference of the wheel, so that the soft iron bars, when the wheel turns, come as close to the poles of the magnets as possible without touching. The bars of soft iron may be eight in number, and the magnets four. Let the wheel and magnets be in the positions in fig. 184, where we are supposed to look at the side of this machine, and only see one pole of each electro-magnet. Let the current circulate round A and B and not round C or D. Then 8 and 3 being nearest

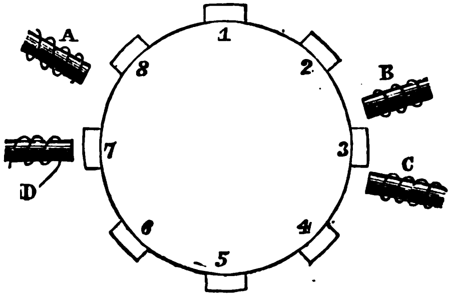


Fig. 184.

to these will be attracted most, and the wheel will turn in the direction of the arrow. As soon as 8 and 3 are opposite to A and B respectively, their circuits are broken, and that of C is completed. The bar 4 is then nearest to C and is pulled up. When it is opposite to C, the current around C is hollow, and that around D is established; the bar 8 is thereby pulled down. When 5 is opposite to D the current round D is broken, and 1 and 4 are ready to be attracted by A and B, whose currents are therefore established. The making and breaking of the currents is automatic at the proper places. It is effected by three cams on the axis of the machine, fig. 185, which on passing press on ivory wheels D, E, F, which are fastened to the ends of springs pressing against

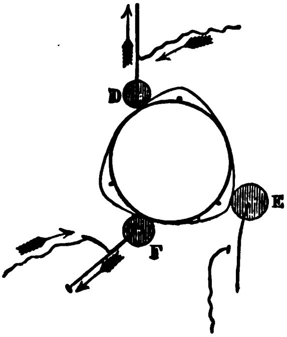


Fig. 185.

the ends of the conducting wires. When the cam lifts the wheel it forces the spring away from the corresponding wire, and breaks the circuit of the corresponding electro-magnet. As long as the wheel is between two cams, the contact is maintained.

238. Other forms of electro-magnetic machines have been devised, but at present they are not in much use. The strength of the current is proportional to the amount of zinc dissolved in the battery that is oxidized, and is proportional to the heat which the oxidation of that zinc would liberate. Now, one pound of carbon when burnt will give as much heat as six pounds of zinc. Apart, therefore, from the fact that some form of carbon must be employed to reduce the zinc from its ore, and that therefore zinc, as long as it is burnt in this way, must be very much dearer than carbon, there is less potential energy in it weight for weight. On the other hand, when carbon is burnt the product of the combustion is lost; while the sulphate of zinc from the battery has commercial value. Further, the whole of the energy of the zinc's combination is found in the current, while a vast quantity, say 90 per cent. of the heat-energy of the coal, escapes by radiation, and in the escape steam of high pressure engines, or in the condensing water of low pressure ones. Favourable to the electro-magnetic engine is also the circumstance that the moment the circuit is complete, the zinc dissolves, and the energy is available, so that the great loss while the steam is being got up is obviated. Unfavourable again is the fact that, while steam when used expansively may be said to act inversely, as the distance of the piston from the bottom of the cylinder, while the electro-magnetic attraction varies inversely as the square of the distance; so that the attraction is only very great when the possible range of motion is very small. In the rotary electro-magnetic engine, the attraction is of course a differential one between the nearest soft iron on one side and the nearest on the other of the electro-magnet. Here force appears to be lost, but is not altogether, so far as we shall see in magneto-electricity, the forcible withdrawing of the further iron tends to check the current, and so diminishes the consumption of the zinc.

239. It is indeed the total alteration of the attraction between two electro-magnets when they are in motion that the practical failure of electro-magnetic machines must chiefly be attributed. There is no limit to the attainable attractive force between electro-magnets at rest even by use of currents of fixed strength. For by increasing the size of the core so that it is always far from saturated with magnetism, and the number of windings of the wire around it, and so increasing also the thickness of the wire, that its resistance remains constant, the magnetism increases in proportion to the number of windings. The attraction between two magnets is the product of their individual magnetisms. The attraction, therefore, between two such equal magnets is proportional to the square of the number of convolutions of the current wire. But when the electro-magnets approach one another, as we shall see in Chap. IX., each electro-magnet seeks to set up in the wire round the other a current which, acting alone, would cause repulsion between the two, and which therefore diminishes the existing current. The very act of motion therefore diminishes the attraction, by diminishing the current strength. This is seen by introducing a tangent galvanometer into the circuit. If, while the current passes, the machine be held still, the needle shows the deflexion proper to a current of that strength. If sufficient work be given to the machine to cause it to labour slowly, the needle turns somewhat towards its normal position. If the machine be relieved of work, so that it spins round, the needle turns almost back to N. and S., showing that scarcely any current is passing. Since the current is proportional to the consumption of zinc, it appears that work done is proportional to the consumption of zinc. It appears, indeed, that if, during the machine's action, the circulating current were to remain constant, no additional mechanical advantage would be gained by increasing the number of convolutions of the exciting helices. And, further, that the maximum mechanical effect is obtained when the machine is doing such an amount of work that the current is thereby reduced just half of the strength which it has when the machine is stopped.

240. Residual Magnetism.—The softer, that is the purer, the iron, the more quickly does it attain its maximum magnetic force when a current circulates around it: and the more quickly does it lose its magnetism when the current ceases. In no case, however, is either the complete magnetization or the complete demagnetization instantaneous. The quantity of magnetism which remains after the current ceases is called the residual magnetism. It is greatest in amount when the electro-magnet is a horse-shoe, and armed with a keeper. As the keeper remains on, residual magnetism lingers for a long time in the system; but on tearing it off, the magnetism is almost entirely destroyed, and is not renewed on restoring the keeper.

CHAPTER VI.

RESISTANCE, CONDUCTIVITY, ELECTRO-MOTIVE FORCE, AND THEIR MEASUREMENT.

241. Linear Resistance.—From Art. 217 *et seq*, Ohm's law, expressing the relationship between the current strength or quantity Q, the electro-motive force E, and the resistance R, is $Q = \frac{E}{R}$ (1), or $E = Q\,R$ (2), or $R = \frac{E}{Q}$ (3). Let us now suppose that we have *n* wires whose resistances are respectively R_1, R_2, R_3,.........R_n. Let these wires be joined end to end, and let the free ends be joined to the poles of a battery which succeeds in sending a current, of strength Q, through the series, and let the resulting electro-motive force be E, which is the sum of the electro-motive forces E_1, E_2, E_3,.........E_n, in each wire. For equation (2), we have—

$$\begin{aligned} Q\,R &= E \\ &= E_1 + E_2 + E_3 + \ldots\ldots\ldots\ldots\ldots + E_n. \\ &= Q\,R_1 + Q\,R_2 + Q\,R_3 + \ldots\ldots + Q\,R_n \\ &= Q\,(R_1, + R_2, + R_3, + \ldots\ldots\ldots\ldots + R_n). \\ \therefore R &= R_1 + R_2 + R_3 + \ldots\ldots\ldots\ldots\ldots + R_n \ldots\ldots\ldots\ldots (4). \end{aligned}$$

Or the resistance of a series of conductors joined end to end is the sum of the individual resistances. The immediate consequence of this rule is, that when the current passes along a cylindrical or other prismatic wire, that is, along a wire whose sectional area is constant, the resistance offered by the wire is directly proportional to its length.

242. Let now the *n* wires of Art. 241 be arranged side by side, and all one set of ends be joined to one pole, and all the other ends to the other pole of the battery. Calling the current strengths or quantities through the respective wires Q_1, Q_2, Q_3,........Q_n, the respective resistances R_1, R_2,.......

R_n, and calling Q the total current, and R the total resistance, we have—

$$Q = Q_1 + Q_2 + \dots\dots\dots\dots + Q_n.$$

$$\text{or } \frac{E}{R} = \frac{E_1}{R_1} + \frac{E_2}{R_2} + \dots\dots\dots\dots + \frac{E_n}{R_n} \dots\dots\dots\dots (5).$$

But since the attachments are at the same points, the electro-motive force for each wire is the same, and the same as that for the collective bundle, or $E = E_1 = E_2 = \dots\dots\dots\dots = E_n$, therefore from equation (5)—

$$\frac{1}{R} = \frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{R_3} + \dots\dots\dots + \frac{1}{R_n} \dots\dots\dots\dots\dots (6).$$

Accordingly, the reciprocal of the resistance of a bundle of wires is the sum of the reciprocals of its constituent wires. Or, if we define conductivity as the reciprocal of resistance, the conductivity of a bundle is the sum of the conductivities of its parts. It is clear from the above that if the resistances of the separate conductors are all equal to one another—

$$\frac{1}{R} = n \frac{1}{R_1}$$

$$\text{or } R_1 = n R.$$

243. We may conceive any prismatic conductor to be made up of an indefinite number of indefinitely narrow unit prisms lying side by side. The resistance offered by a prism being inversely proportional to the number of such unit prisms which it contains, and this number being proportional to the sectional area of the prism, it follows that, when the chemical nature and lengths of two wires are the same, their resistances are to one another inversely as their sectional areas. If the prisms are similar, that is, if their transverse sections are similar plane figures, their resistances, of course, are inversely as the squares of the homologous lines of those plane figures, that is, if they are cylindrical wires, inversely as the squares of the radii, or diameters, or circumferences, etc.

The resistance of a wire (cylindrical or otherwise prismatic), accordingly, varies directly with its length, and inversely *with its* sectional area.

244. Suppose, then, a wire of length 1 has an *n*th of its length doubled back on the rest of the wire, and we wish to find the total resistance of the folded wire (fig. 186). Let the resistance of the original wire unfolded be R. Let the resistances of the two parts of the folded wire be R_1 and R_2 respectively. Let R' be the total resistance of the folded wire. Then $R' = R_1 + R_2$

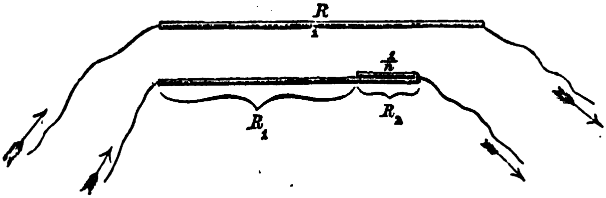


Fig. 186.

$$\frac{R_1}{R} = 1 - \frac{2}{n}$$

$$\text{or } R_1 = R\left(1 - \frac{2}{n}\right)$$

$$\text{and } \frac{R_2}{R} = \frac{1}{2n}$$

$$\text{or } R_2 = R\frac{1}{2n}$$

$$\therefore R' = R\left(1 - \frac{2}{n} + \frac{1}{2n}\right)$$

$$= R\left(\frac{2n-3}{2n}\right) \text{..................(7).}$$

Thus, if the wire be folded in half, $n = 2$, and the expression becomes—

$$R' = \tfrac{1}{4}R$$

If one-third of the wire be folded back $n = 3$, and we have—

$$R' = \tfrac{1}{2}R$$

So if $\frac{1}{2 \cdot 25}$ of the wire be bent back—

$$R' = \tfrac{1}{3}R$$

Inversely, if we wish to know how much (what fraction) of the wire must be bent back upon itself, in order that the resistance may be diminished in a given ratio, we may argue as follows:—Suppose we wish to find what fraction of the wire must be folded back so as to make the resistance $\frac{1}{m}$th of what it was, so that $\frac{R'}{R} = \frac{1}{m}$; then from equation (7)—

$$\frac{1}{m} = \frac{2x-3}{2x}$$

where x is the fraction of the lengths required. From this we find—

$$x = \frac{3m}{2(m-1)} \quad \text{(8).}$$

Thus, if we wish to make the resistance $\frac{1}{3}$ of its original amount $m = 3$, and therefore $x = 2{\cdot}25$, or we must turn back $\frac{1}{2{\cdot}25}$ of the length of one end. In the same way, it is easy to find the fraction of the whole length which must be folded back in order to get any fraction not less than $\frac{1}{4}$ of the original resistance.

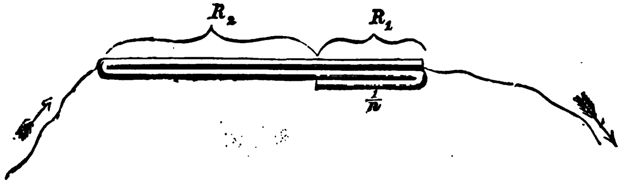


Fig. 187.

245. If we wish to offer a resistance less than $\frac{1}{4}$ of the original, we may fold the wire in such a way that one part of it is doubled, and the other three folded, fig. 187. Let $\frac{1}{n}$th of the wire be folded and the remainder again folded in its middle. The resistance of the wire when straight being R, and calling R_1 and R_2 the resistances of the two parts separately, then the joint resistance $R' = R_1 + R_2$—

$$= R\,\tfrac{1}{3}\,\frac{1}{n} + R\,\tfrac{1}{2}\left(\tfrac{1}{2}\left(1-\frac{1}{n}\right)-\frac{1}{n}\right)$$

$$= R\,\frac{3n-5}{12n} \quad \text{(9).}$$

Thus, if $n = 3$, $R' = \frac{1}{9}R$, as we see at once from the circumstance that then the conductor has $\frac{1}{3}$ the length, and 3 times the sectional area. If $n = 5$—

$$R' = \tfrac{1}{6}R$$

If n increases indefinitely, the number 5 vanishes by comparison, and we obtain the value $R' = \frac{1}{4}R$, for then the wire is simply folded once in its middle point. As before, if we wish to know what fraction must be folded down so that when the remainder is folded in its middle, the joint resistance may bear a predetermined ratio to the original resistances

$$\frac{R'}{R} = \frac{1}{m} = \frac{3\,x-5}{12\,x}$$

$$\text{whence } x = \frac{5\,m}{3\,m-12} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (10).$$

Thus, if we wish to make the resistance $\frac{1}{8}$ of that of the straight wire, substitute 8 for m in equation (10), and we find $x = 3\frac{1}{3}$ or $\frac{1}{3 \cdot 333}$ of the wire being creased down, the remainder is doubled in the middle, and the condition required is fulfilled.

246. In general terms, if the wire, whose resistance when straight is R, be folded so that there are m parts of which $m - 1$ are equal, and the last is $\frac{1}{n}$th of the total length, then the total resistance $R' = R_1 + R_2$—

$$= \frac{1}{m\,n} + \frac{1}{m-1}\left(\frac{1-\frac{1}{n}}{m-1} - \frac{1}{n}\right)$$

$$= R\,\frac{m\,n-2\,m+1}{m\,n\,(m-1)^2} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (11).$$

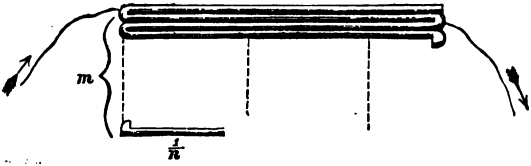
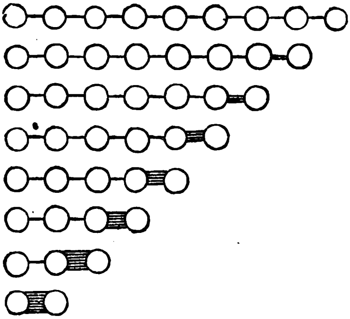


Fig. 188.

This equation, it will be seen, becomes equation (7) or (9) according as m is made $= 2$ or 3.

247. In the two subjoined figures the circles denote places of no resistance, such as are practically furnished by cups of mercury. We may suppose the wire to be made up of eight equal lengths, whose ends dip into the mercury. The two figures show 13 different possible combinations from which others may be easily deduced.



$R = 1 = 1.$

$R' = \frac{13}{16} = 0{\cdot}812.$

$R' = \frac{16}{24} = 0{\cdot}666.$

$R' = \frac{17}{32} = 0{\cdot}531.$

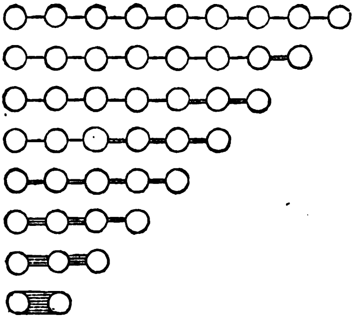
$R' = \frac{16}{40} = 0{\cdot}400.$

$R' = \frac{13}{48} = 0{\cdot}271.$

$R' = \frac{8}{56} = 0{\cdot}143.$

$R' = \frac{1}{64} = 0{\cdot}016.$

Fig. 189.



$R = 1 = 1.$

$R' = \frac{13}{16} = 0{\cdot}812.$

$R' = \frac{10}{16} = 0{\cdot}625.$

$R' = \frac{7}{16} = 0{\cdot}437.$

$R' = \frac{4}{16} = 0{\cdot}250.$

$R' = \frac{7}{48} = 0{\cdot}146.$

$R' = \frac{1}{16} = 0{\cdot}062.$

$R' = \frac{1}{64} = 0{\cdot}016.$

Fig. 190.

248. Divided Currents.—Let, as in Art. 241, there be a *bundle of* wires of resistances R_1, R_2, R_3, etc., having all their one set of ends fastened to one pole of a battery, and all their other ends to the other. Let the electro-motive force, which is common to all, be E. The current will divide and pass along each wire in quantity depending upon the resistance of the wire. Let the total resistance be R, the total current Q, and the currents in the individual wires, Q_1, Q_2, etc. The electro-motive force is the same for each wire and for all, so that

$$\begin{aligned} E &= Q\,R. \\ &= Q_1\,R_1. \\ &= Q_2\,R_2. \\ &\text{etc.} \end{aligned}$$

$$\therefore\ Q_1 = Q\frac{R}{R_1} \quad \text{..................(12).}$$

$$Q_2 = Q\frac{R}{R_2}.$$

$$Q_3 = Q\frac{R}{R_3}.$$

$$\text{etc.}$$

Whence the current through any of the branches of a divided current is known when we know the total current, the total resistance, and the resistance of the branch under consideration. The comparative strength of the current in two such branches is independent of their absolute strengths, and is got by dividing equation (12) by the next one, giving

$$Q_1 = Q_2\frac{R_2}{R_1} \quad \text{..................(13).}$$

which equation is of the greatest use in electrical measurement.

249. Potential at different points of a Conductor.—Difference of level bears the same relation to pressure in a hydrostatic system, as difference of potential bears to electromotive force in an electric one. Again, electric potential is directly comparable with tension; for tension is proportional to the pressure which is producing it. Accordingly, if the two extremities of a conducting wire have the same potential, the electro-motive forces along that wire will be equal and opposite. In other words, there is no resultant electromotive force between the points, and no current passes. In all cases, just as in mechanical problems, two equal and opposite forces may be withdrawn or added without altering the conditions; so we may suppose that any wire, through which no current is passing, is simultaneously traversed by equal and opposite currents. In doing so, we should, however, be obliged to lose sight for a moment of the generally received "explanation" of current motion, namely, difference of potential, which is after all only a mode of expression.

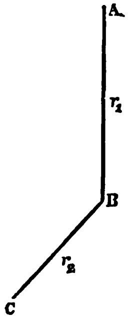


Fig. 191.

Let a current, of strength Q, pass along a conductor A B C, which is made up of two parts, AB having the resistance r_1, and BC having the resistance r_2. The total resistance, R, offered to the current is then $r_1 + r_2$. Let the potential at A be p_a, that at B be p_b, and that at C be p_c. Then the electro-motive force, by dint of which Q moves from A to B, is $p_a - p_b$. The electro-motive force in B C is $p_b - p_c$, and the electro-motive force in the whole conductor is $p_a - p_c$. Since the electro-motive force is the product of the current and the resistance, we have

$$p_a - p_b = r_1 \text{ Q} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots(\alpha).$$
$$p_b - p_c = r_2 \text{ Q} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots(\beta).$$
$$\therefore p_a - p_c = (r_1 + r_2) \text{ Q} = \text{RQ}.$$

From

$$\text{R} = r_1 + r_2$$

we get

$$\text{R}p_b = r_1 \, p_b + r_2 p_b$$

thence by means of (β) and (α)

$$= r_1 \, (r_2 \text{ Q} + p_c) + r_2 \, (p_a - r_1 \text{ Q})$$
$$= r_1 \, p_c + r_2 \, p_a.$$

$$\text{or } p_b = \frac{r_1 \, p_c + r_2 \, p_a}{\text{R}} \ldots\ldots\ldots\ldots\ldots\ldots(14.)$$

From which the potential of the middle point B is known in terms of the extreme potentials and the two resistances only.

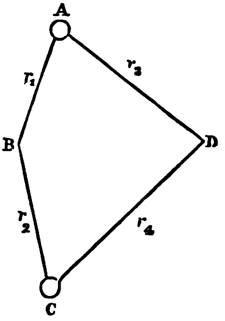


Fig. 192.

Let us take another couple of wires, A D, D C, having the respective resistances r_3 and r_4, and joint resistance R′, and having the same potential as before both at A and C, which causes a current Q′ to traverse them. The potential at D or p_d is found as before.

$$p_d = \frac{r_3 p_c + r_4 p_a}{R'}$$

In order that p_b may be equal to p_d we must have

$$\frac{r_1 p_c + r_2 p_a}{R} = \frac{r_3 p_c + r_4 p_a}{R'}$$

If C be at the zinc end of the battery $p_c = 0$, whence putting their values for R and R′ we have

$$\frac{r_2 p_a}{r_1 + r_2} = \frac{r_4 p_a}{r_3 + r_4}$$

$$\text{or } r_2 r_3 = r_1 r_4 \text{ or } \frac{r_1}{r_3} = \frac{r_2}{r_4} \ldots\ldots\ldots\ldots\ldots\ldots (15).$$

That is, the products of the pairs of resistances opposite to one another must be equal.

250. Wheatstone's Balance or Bridge.—If the points B and D are joined by a wire, no current will pass along the wire when the condition of equation (15) is satisfied, and under no other condition. If therefore B and D are connected with the two terminals of a galvanometer G, fig. 193, and A and C with the platinum and zinc plates of a cell or battery, the needle of G remains at rest under the above conditions. If, say, r_3 is diminished, some of the current will pass from D to B, and the needle will turn. This will be prevented by so increasing r_2 or diminishing r_4, or by doing both, that the above ratio is preserved. This gives us an immediate and incalculably useful means of comparing resistances, and so of measuring resistances by comparison with a standard. In the resistance bridge, or Wheatstone bridge, the simplest method of use is shown in fig. 194. The

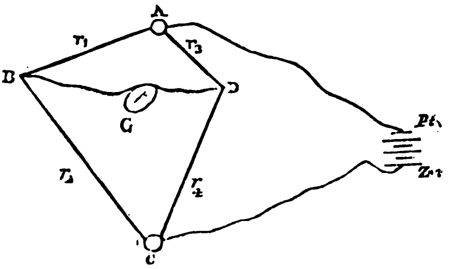


Fig. 193.

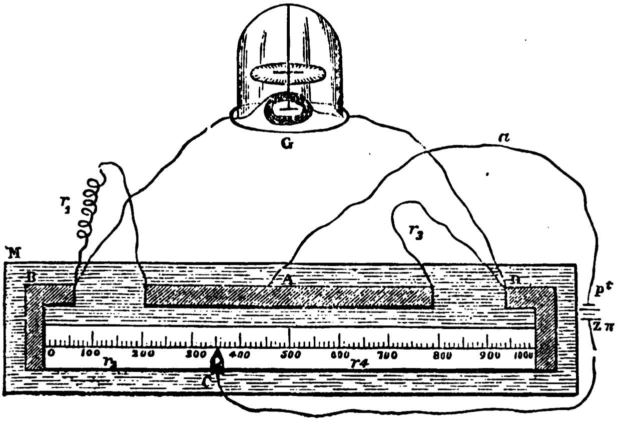


Fig. 194.

figs. 193 and 194 are lettered homologously. Upon a varnished wooden board M is stretched a wire r_2 r_4, of uniform thickness and free from flaws. This is usually made of German silver, because the resistance of this metal is but little affected by heat. Sliding upon this is an ebonite block *c*, provided with a pin, which is connected with one pole of the battery, and which is kept up by a spring from touching the wire, but which may be pressed down so as to make contact. The wire $r_2\,r_4$ is, say, one metre long; C carries a pointer which slides along a scale S divided into millimetres. By reading this scale the relative lengths of r_2 and r_4 are determined. The ends of the wire $r_2\,r_4$ are soldered to two pieces of brass B and D, which are so massive as to offer no sensible resistance. A is a similar piece. The galvanometer G is connected with B and D, and A is connected with the other pole of the cell or battery by the wire *a*. Between B and A is the resistance r_1, and between D and A the resistance r_3. As we do not require to measure the current through the galvanometer, but to reduce that current to zero, it is usual to use a light astatic galvanometer similar to that sketched in Art. 108, and which is more fully described in Art. 277. The method of fastening the wires is not shown in the figure.

Suppose we wish to measure the relative resistances of r_1 and r_3. Make the connections as above. Move C along the wire, and at different places, press down the pin so as to complete the battery circuit. A place will at last be found where the needle ceases to turn, then $\frac{r_1}{r_3} = \frac{r_2}{r_4}$, that is, as the length of the wire r_2 is to the length of the wire r_4.

251. Experiments with the Electric Balance.—A few instances may here be given illustrating the use of the bridge in confirming some of the results given in the previous paragraphs of this chapter. If two exactly equal, and in every way similar, pieces of wire be introduced between B and A, and A and D, the block *c* has to be put at 500, in order that the needle may not be deflected. If the wire BA be twice as long as AD, but otherwise identical, *c* must be placed at 666·6. If, while one wire is between A and D, two similar wires are put side by side between B and A, then *c* must be placed at 333·3. If the length of a wire between A and D is known, the length of a piece of similar wire between B and A can be determined with accuracy to within $\frac{1}{10000}$ of its length. If we have two wires of the same material, but of different lengths, l_1 l_2, and different diameters d_1 and d_2 respectively, their resistances are found to have the relation

$$\frac{R_1}{R_2}=\frac{l_1\,d_2^2}{l_2\,d_1^2}$$

As it is difficult to determine very exactly the diameters of very narrow wires, they may be deduced from the weights, w_1 and w_2, of known lengths

$$\frac{w_1}{w_2}=\frac{l_1\,d_1^2}{l_2\,d_2^2} \text{ or } \frac{d_1^2}{d_2^2}=\frac{w_1\,l_2}{w_2\,l_1}$$

whence

$$\frac{R_1}{R_2}=\frac{w_2\,l_1^2}{w_1\,l_2^2}$$

Inversely, the relative diameters of two wires can be deduced from their weights, lengths, and resistances.

252. Unit of Resistance.—In the above examples, resistances have been compared among themselves; and by such simple means many of the laws of resistance have been deduced. For recording resistances, so as to convey a sense of their amount, it is necessary to adopt some standard or unit. However derived, the electrical unit is arbitrary, like all measures of length, weight, time, etc. The resistance offered by a metallic wire varies with the length, thickness, temperature, chemical nature, and physical condition of the wire. So that not even equal lengths of platinum wire at the same temperature will show equal resistances. If one of the two wires be not so thoroughly annealed as the other, their resistances will not be equal. The slightest quantity of a foreign metal will entirely destroy equality. In one system of units, a column of perfectly pure mercury, one metre high, and having a sectional area of one millimetre, is taken at 0°C. as having 1 unit of resistance. This standard has the advantage of being always recoverable with ease and very considerable accuracy. It is only necessary to have a tube of uniform bore, to measure the length, and to weigh the mercury in it. From these data, and from the specific gravity of mercury, the sectional area of the column is found, and thence, by one of the above formulæ, the ratio of the resistance of this column to the ideal column of 1 meter high, and 1 square millimeter base. A German silver wire balanced against this on the bridge will then serve as a permanent unit.

The unit more frequently used is the Ohm or B. A. unit, which is 1·0401 times as great as the metre-millimetre-mercury unit. The Ohm has been derived from the relation between a current, the mechanical force it exerts on a magnet, the distance of the magnet and its strength. We cannot here describe the method in full which is employed for examining the relation. But it may be understood from the following considerations.

It is found by experiment that the mechanical force f exerted by a current on a magnet depends entirely upon (1) the strength of the current or Q; (2) on the length d of the conductor through which the current is passing; (3) upon the distance d between the current and the magnet, and (4) upon the strength of the magnet m, and that—

$$f = \frac{Q\,l\,m}{d^2}$$

$$\text{or } Q = \frac{f\,d^2}{l\,m} \quad \ldots\ldots\ldots\ldots\ldots\ldots(1).$$

The strength m of the magnet can be defined in terms of mechanical force, and deduced from the mass of the magnet and its rate of oscillation when suspended and thrown out of the meridian.

Further, the work done by a current varies directly as the square of the current strength, directly as the resistance which the circuit offers, and directly as the time, or—

$$W \doteq Q^2\,r\,t$$

$$\text{or } r = \frac{W}{Q^2\,t} \quad \ldots\ldots\ldots\ldots\ldots\ldots(2).$$

Here the work done is measured by the mass of the magnet displaced, and its angular displacement against its inertia, and the directive magnetism of the earth. It is seen, that in the last equation, the resistance is expressed in terms of time, work, and current strength. From equation (1) current strength is expressible in terms of mechanical force, distance, length, and again mechanical force. Accordingly, resistance is expressible entirely in terms of weight, time, and length. Taking 1 second as unit of time, 1 metre as unit of length, and 1 gram as unit of weight, an "absolute" unit of resistance is obtained by employing the above equations, and this multiplied by one hundred million, or, in other words (10^7), is the Ohm or B. A. unit. From the work done by the current in the experimental wire, the resistance in that wire is found, and this resistance is considered unity when the above measures are units, namely, 1 second time, 1 metre space, and 1 gram weight or force.* This is a hundred millionth of an Ohm. A megohm = 1 million Ohms, a microhm = 1 millionth Ohm.

It is, of course, requisite that standards of resistance should be made and kept with the same care as all those of length. Failing perfect accuracy in their manufacture, they become empirical standards of resistance just as the standard meter, though based upon a measurement of an arc of a meridian is really an empirical length. I know of no natural magnitudes but those of number and angle.

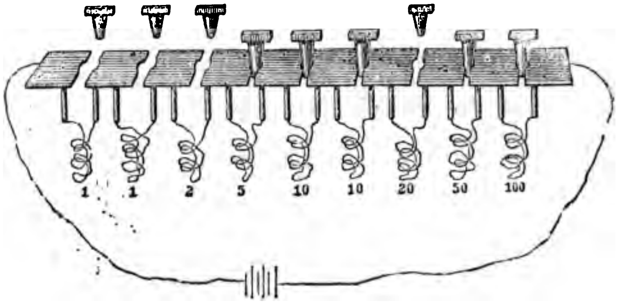


Fig. 195.

253. Resistances are generally in the form of coils of German silver wire, called resistance coils. The wire is covered with silk and rolled on a reel, which may then be steeped in melted paraffin. The coils are fastened with each terminal to a brass plate, and these plates are arranged in a line with short intervals between each, which may be bridged over by introducing brass pins. We may suppose, fig. 195, the coils to have resistances represented by the accompanying figures in Ohms. Some of the pins are in their places, and some are represented withdrawn. The resistances represented in the figure between A and B is 24 Ohms. The resistance, as we shall see, varies with the temperature, so that the resistance can only be correctly represented when the temperature is that at which the standard resistances were made.

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* The force actually taken as unity is $\frac{1}{9.81}$ gram, for this force acting on 1 gram for 1 second will give it a velocity of 1 meter a second.

254. Specific Resistance.—We have hitherto considered only the effect upon resistance of variation in the length and thickness of the wire, that is, we have supposed the wire to be of the same material. To find the effect which difference of chemical nature takes upon the resistance, we might, of course, examine the resistances of exactly equal lengths of wires of equal thicknesses of the two metals, say steel and copper. It is not necessary that the two should be brought to geometrical equality if we can measure their lengths and thicknesses. The former can be done with great relative exactness if the length be considerable, the latter may generally be deduced most exactly from weight and specific gravity. Thus, a steel wire l_1 meters long, weighs w_1 grams, and has a resistance of 0_1 Ohms, a copper wire l_2 meters long, weighs w_2 grams, and has a resistance of 0_2 Ohms. Let the sectional area of the steel be a_1, that of the copper a_2. Let the specific gravity of the steel be sp_1, that of the copper sp_2.

$$\text{Then } \frac{w_1}{w_2} = \frac{l_1 a_1 sp_1}{l_2 a_2 sp_2} \quad \text{or, } \frac{a_1}{a_2} = \frac{w_1 l_2 sp_2}{w_2 l_1 sp_1}$$

Resistance of steel of section a_1, and length $l_1 = o_1$

$$\therefore \quad ,, \quad a_2, \quad ,, \quad l_2 = o_1 \frac{a_1 l_2}{a_2 l_1} = o_1 \frac{w_1 l_2^2 sp_2}{w_2 l_1^2 sp_1}$$

$$\therefore \frac{\text{Resistance of steel of any length and section}}{,, \quad \text{copper ,, same} \quad ,,} = \frac{o_1}{o_2} \cdot \frac{w_1 l_2^2 sp_2}{w_2 l_1^2 sp_1}$$

And so the comparative resistances of metals *in the abstract* have been determined. Taking, then, the resistance of any length and thickness of silver wire as unity, and dividing by this the resistance of the same length and thickness of a wire of another metal, we get the specific resistance properly so called of that metal in regard to silver. Making the use of the electric bridge described in Art. 250, the wire to be measured is placed at r_3, any convenient number of Ohms of the resistance introduced at r_1, and the two resistances balanced as before described. Taking silver as having the resistance 1, the following numbers have been deduced. In column (2) the reciprocals of the resistances or conductivities are given, taking the conductivity of silver as 100. In column (3) is given the actual resistance in microhms offered by one cubic centimeter of each metal.

	Specific resistance Silver = 1 (1).	Specific conductivity. Silver = 100 (2).	Absolute resistance of 1 cubic centimeter in megohms (3).
Silver,	1·000	100·0	1·521
Copper,	1·001	99·9	1·616
Gold,	1·250	80·0	2·081
Aluminum,	1·786	56·0	2·945
Sodium,	2·674	37·4	...
Zinc,	3·448	29·0	5·689
Cadmium	4·219	23·7	...
Potassium,	4·808	20·8	...
Platinum,	5·555	18·0	9·158
Iron,	5·946	16·8	9·825
Tin,	7·633	13·1	13·36
Lead,	12·048	8·3	19.85
German Silver,	13·177	7·7	21·17
Antimony,	21·739	4·6	35·90
Mercury,	62·500	1·6	99·74
Bismuth,	83·333	1·2	132·7
Carbon,	1428·571	1·07	..

255. Alloys of the above metals generally show a resistance greater than the mean of the resistances of their consituents. An alloy of 2 parts by weight of gold and 1 of silver has a greater resistance than gold alone, and all alloys of gold and silver, which are in about this proportion, have nearly the same resistance. Hence, such a proportion is recommended for making standard resistances. Moreover, alloys are, as a rule, less affected in their resistances by change of temperature than are their constituents. Accordingly, and on account of its considerable resistance, standard coils may be made of German silver.

256. The resistance of a metallic wire increases invariably as the temperatue rises, but for equal increments of temperature the increase is less at higher temperatures than at lower ones. Empirical formulæ have been constructed containing arbitrary constants which give calculated resistances very closely in accord with the experimentally determined resistances through long ranges of temperature. But at present our data are not sufficient to prove that the same formulæ would serve at the highest temperatures, and so furnish an exact pyrometer; still, calibrated with an air thermometer, it may furnish a compact instrument, and exact within the range of the latter. The general form of the formulæ is

$$\mathrm{R} = a\ \mathrm{T}^{\frac{1}{2}} + b\ \mathrm{T} + c,$$

in which T is the absolute temperature C (number of degrees above − 273) and a, b, and c are constants, different for each metal, thus for iron

$$\mathrm{R} = 0{\cdot}07254\,\mathrm{T}^{\frac{1}{2}} + 0{\cdot}0038133\,\mathrm{T} - 1{\cdot}23971.$$

The increase is therefore very considerable. If a platinum wire be introduced into a circuit with a tangent galvanometer and then heated, the current is immediately seen to be weakened, this is shown by the diminished deflexion of the needle. The effect is more marked by making the wire to be heated, one of the resistances in Wheatstone's bridge, and heating it after the galvanometer is balanced. It is by the latter way that the effect of heat on metallic conductors has been measured. (See Chap. X.)

257. Resistance of Liquids.—We are apt to conceive that heat so separates the parts of a solid that electricity cannot, so readily as before, pass from one part to the next, so that the resistance is increased. While in liquids heat, by causing the parts to have greater facility in motion, enables electricity to be communicated. This conception is, however, probably unjust; for heat diminishes the conductivity of the liquid mercury. Again, the solid glass when heated below red heat conducts freely, although at ordinary temperatures it is a non-conductor. The imperfect conductors, such as the metallic sulphides and oxides, conduct better when heated. As long as these compound bodies are not fused they conduct the current without decomposition, but when fused a portion of the current passes through them without decomposing them, but another part effects electrolysis; or rather the amount of electrolysis is not proportional to the current strength. If, instead of igneous liquefaction or fusion, we employ solvent liquefaction or solution, so very little of the current passes through without affecting electrolysis that, as we saw in Art. 223, the amount of gas in the Voltameter is taken as an exact measure of the current. It seems that when a feeble current passes through an electrolyte, a very small part of it may do so without doing chemical work, but that this part is so small that we may neglect it. The practical difficulty of measuring liquid resistances is very considerable, because electrolysis so often polarises the electrodes that the electro-motive force varies very rapidly. We may divide a long trough into three cells by means of two porous partitions. Into one end cell, sulphate of zinc and an amalgamed zinc plate are put; into the other sulphate of copper and a copper plate, the zinc and copper plate are connected by means of a galvanometer, and different liquids are placed in the central cell. The electro-motive force is here constant, so is the external resistance. The internal resistance is made up of the resistance of the sulphate of copper, that of the sulphate of zinc, and that of the liquid under examination. The effect on the current strength of

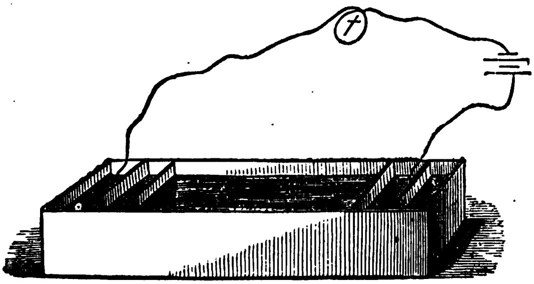


Fig. 196.

the intermediate liquid may be found by examining the increase in the current strength, which is brought about by substituting mercury for the intermediate liquid, whereupon the internal resistance is diminished. Metallic silver conducts 10^9 times as well as distilled water. It is remarkable that the minimum resistance of a salt solution is not found to be near the point of saturation, but a solution of a certain strength conducts better both than a stronger and than a weaker one. Thus water has about 746,300 times the resistance of mercury. H_2SO_4 about 96,950, $H_2SO_4 + 14H_2O$ about 14,157, $H_2SO_4 + 13H_2O$ about 13,310, and $H_2SO_4 + 499H_2O$ 134,773. The least resistance of a solution of sulphate of zinc is the solution consisting of about $ZnSO_4 + 24H_2O$. The solution of sulphate of copper consisting of $CuSO_4 + 45H_2O$ has the least resistance. Some of the solutions which show minimum resistance exhibit the water and the salt in the same proportions as they exist in the cryohydrate; that is, the hydrate which is formed from a saturated solution at a temperature below zero.

258. Unit of Electro-motive Force.—This is defined as the electro-motive force which is competent to send a current of unit strength through a unit resistance, and thereby send a unit quantity in a unit time. We have already considered a unit current, Art. 252, to be the current which, in passing through a conductor of unit length, exerts a unit of force on a unit magnetic pole at a unit distance. And a unit of work, or its equivalent, is done per second by a unit current passing through a conductor of unit resistance. The unit of electro-motive force, which is 100,000,000 absolute units, is called a Volt, and the electro-motive force of one Daniell's cell is equal to 1·08 Volt. One million Volts is a megavolt, and one-millionth of a Volt is a microvolt. A unit of quantity is the quantity of electricity which will flow through a conductor whose resistance is 1 Ohm in one second, when the electro-motive force is 1 Volt. This quantity is called a weber, and it is competent to decompose 0·00009 grams of water; since this quantity contains 0·00001 grams of hydrogen, this is the weight of that gas liberated. An equivalent quantity of every other element will be liberated by a Volt.

259. Comparison of Electro-motive Forces.—If we wish to compare the electro-motive forces of two cells, such as a Daniell's and a Groves', we get all the requisite data by the simple use of the rheostat and the tangent galvanometer. For when these two instruments are inserted in the circuit of the Grove a certain deflexion θ is observed. Then

$$\tan\theta=\frac{E_1}{R_1}.$$

Introduce more wire of the rheostat till the angle is θ_1, and let the additional length of resistance be l_1—

$$\tan\theta_1=\frac{E_1}{R_1+l_1}$$

Now if we replace the Grove by a Daniell, we must alter the resistance of the rheostat till we get the first deflexion θ—

$$\tan\theta=\frac{E_2}{R_2}.$$

Add now the additional resistance l_2 until the deflexion θ_1 is again reached, then

$$\tan\theta_1=\frac{E_2}{R_2+l_2}$$

$$\therefore \frac{E_1}{R_1+l_1}=\frac{E_2}{R_2+l_2} \text{ or } \frac{R_1}{E_1}+\frac{l_1}{E_1}=\frac{R_2}{E_2}+\frac{l_2}{E_2};$$

whence

$$E_1=E_2\frac{l_1}{l_2}$$

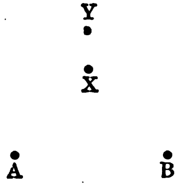
or the electro-motive forces are in the proportion of the lengths of resistance added. The electro-motive forces of a few combinations are here given :—

		VOLTS.
DANIELL	Amalgamated zinc with $H_2SO_4+4H_2O$ and Cu with saturated $CuSO_4$	1·08
	,, $H_2SO_4+12H_2O$,, ,, ,,	0·978
	,, $H_2SO_4+12H_2O$,, ,, $Cu2NO_3$	1·00
BUNSEN	,, $H_2SO_4+12H_2O$ and C with HNO_3..........	1·964
GROVE	,, $H_2SO_4+4H_2O$ and Pt with HNO_3..........	1·956
CLARK	,, $Hg_2SO_4+ZuSO_4$ and H_g with $H_{g2}SO_4+ZuSO_4$	1.457

260. Distribution of Current in Continuous Conductor.—In Art. 248, we have seen that in a divided current or *multiple arc,* when the electro-motive force of one and all is E, the total resistance is R, and the resistance of one branch is R_1, then the current Q_1 in that branch is

$$Q_1 = Q\frac{R}{R_1}$$

Imagine a thin but unbounded sheet conductor to receive at one point a current of electricity, and to discharge it at another. The motion of the electricity would be closely analagous to that of water, which entered a boundless shallow tray at one point and left it at another. If the water had no mass, each particle of it would move in a circular arc passing through the two points, and having its centre on the straight line bisecting, and at right angles to the straight line joining them.



To find the geometric position of two points to one another on the conducting plane, such that no current passes between them, when two other points are the electrodes, let A and B be the electrodes, and X and Y the points between which no current passes that is of equal potential, the potential at $X = \text{const. X}\frac{AX}{BX}$ and by the condition $= \text{const. X}\frac{AY}{BY}$, so that $\frac{AX}{BX} = \frac{AY}{BY}$ is the condition of equipotential between X and Y. The line joining all the points which satisfy this condition is a circle whose centre is on the axis of A B. The family of curves which cut these circles at right angles are the lines of force or flow, and these are also circles. That these latter circles are the lines of flow may be shown by cutting the tin-foil along one or more of them, the resistance is not thereby increased; while if the cut be made across them the current is checked. Again, if we strew iron filings on a sheet of tin-foil pasted on glass, and send a current between two electrodes on the edges while the plate is being tapped, the filings arrange themselves in circles, as in the figure, each particle setting itself with its larger axis at right angles to the flow through that point. The filings, in short, trace out the equipotential lines. If the poles from a battery are brought to two points on the horizontal edge of a large sheet of zinc standing vertically in the magnetic meridian, and a very short magnetic needle be hung as close as possible to the sheet of zinc, and at equal distances from the two poles, the current in the zinc will turn the

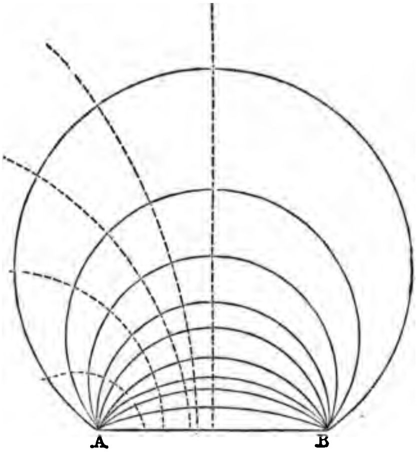


Fig. 197.

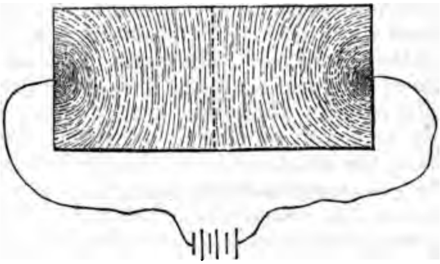


Fig. 198.

needle one way round, when the needle is near the upper edge, and the other way when it is lower down. At a point *from the edge*, about one-third of the line joining the poles, the needle is at rest. The currents below these take an equal and opposite effect to the higher currents. The currents below the needle are the more numerous, but traversing longer arcs, they are weaker, their average distance from the needle is greater, and a larger part of their motion is vertical.

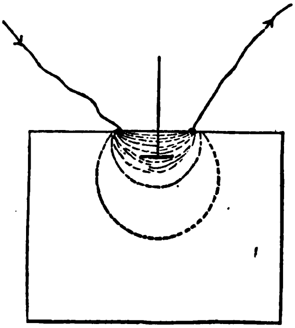


Fig. 199.

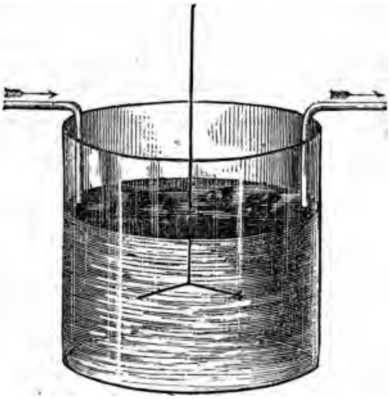


Fig. 200.

A similar reversal of the needles turning is shown when the needle is covered with paraffin, and hung by a silk thread in a conducting liquid. The battery poles just touch the liquid. If the needle be hung above the liquid it turns, of course, in the well-known manner due to the current passing beneath it. If it be hung just below the surface, instead of turning in the opposite direction, which it would do if the current passed straight only from pole to pole, it turns in the same direction as before, as though a single current passed beneath. This is of course due to the difference between the joint effects of the higher and the lower currents. A neutral position is found at a distance below the surface of about one-fourth the distance of the poles apart.

CHAPTER VII.

MECHANICAL RELATION OF CURRENTS.

261. Attraction and Repulsion of Currents.—Currents attract one another when they move in the same direction, and repel one another when they move in opposite ones. This crude assertion may serve as the first rough statement of the rule which we shall have to examine. If we have two currents, *a* and *b*, in one plane, and the paths of these currents

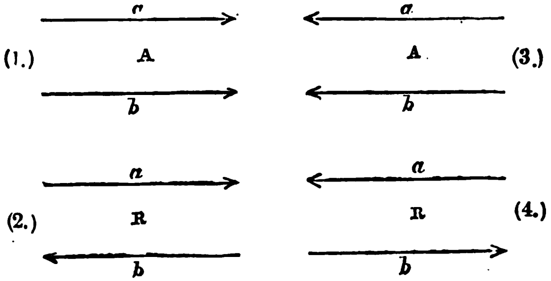


Fig. 201.

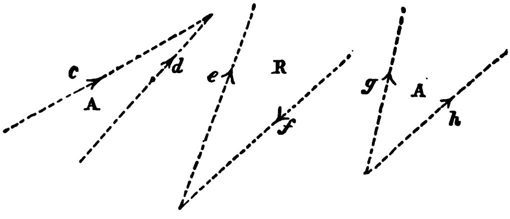


Fig. 202.

are parallel, then there will be attraction in (1) and (3), repulsion in cases (2) and (4). Every part of *a* in (1) and (3) attracts and is attracted by every part of *b*. In (2) and (4), there is repulsion between every part of *a* and every part of *b*. Consider now two short currents in the same plane, but inclined to one another, prolong the direction of each both ways, fig. 202. If the prolongations, both in the directions of the currents, meet (*c*, *d*), or both in the opposite directions (*g*, *h*), there will be attraction. If (*e*, *f*) they meet when one is produced in the direction of the current and the other in the opposite direction, then there will be repulsion.

Perhaps this rule is more clearly stated as follows:— Produce the directions of the elementary currents till they meet, then if both currents are directed towards, or both away from the point of intersection, there will be attraction; if one is directed to and the other away from this point there will be repulsion.

The attraction and repulsion of parallel currents is exhibited experimentally by the frames of wires shown in fig. 203.

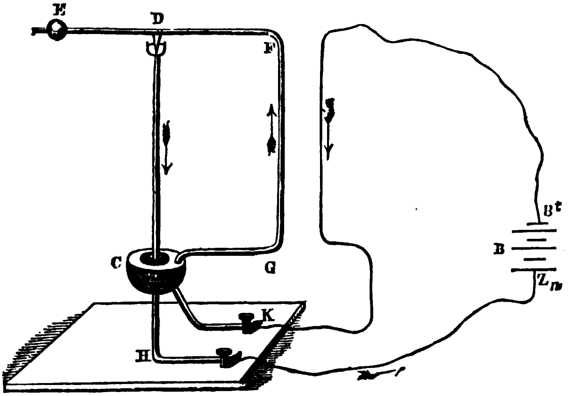


Fig. 203.

Through the centre of a mercury cup C, but protected from the mercury, passes a brass rod D C H, which supports the mercury cup. A wire bent into a D shape, E D F G, is balanced at D on a pivot, which rests in the mercury cup on the top of H D. One end of this wire is counterpoised at E, the other plays in the annular cup of mercury at C. The mercury of C is in contact with a fixed wire K which pierces the bottom of C. K and H are connected with a battery B, and one of the battery wires is brought in a vertical line near F G. In the figure the current in F G and in the neighbouring wire are in opposite directions, and there is repulsion. Attraction ensues on inverting the battery wire. The wire E D F G may be thus chased or pulled round. Here all the elements of the two currents act together.

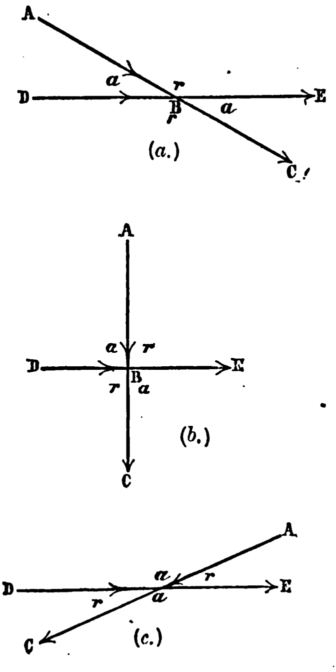


Fig. 204.

262. Let us consider now two currents of sensible length and inclined to one another, and as near as possible in the same plane. First, fig. 204 (*a*), let the currents AC and DE cross (geometrically) at B. Conceive A C to be made up of AB and BC, also DE to be made up of DB and B E. Then between AB and DB, and between B E and BC there is attraction; while there is repulsion between A B and B E, and also between D B and B C. The currents will endeavour by all these relations to close like a pair of scissors around B as a pivot. The same effect will be produced if the currents are, fig. 204(*b*), at right angles to one another, of if they are inclined at any other angle (*c*). These endeavour to get parallel and in the same direction.

Next, fig. 205 (1), let the current A only come as far as D E, then between A and D B there is attraction, and between A and B E repulsion. We may admit that the vertically resolved part of the attraction is equal to the vertically resolved part of the repulsion; but there remain the two horizontally resolved parts of the two. If, therefore, D E is fixed and A free to move, it will not be urged to or from D E, but will be urged to slide horizontally from E to D. If A be fixed, D E will tend to move in the direction of the current it carries, namely from D to E. If, fig. 205 (2), the current B C is moving away from B, there will by similar reasoning be a tendency of B C to slide, keeping parallel to itself, but in the direction of D E. And D E will be urged in the direction from E to D.

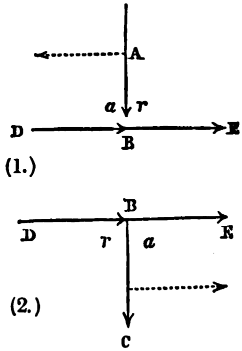


Fig. 205.

263. If the currents are not in one plane, as A B C and D B′ E, fig. 206, we can draw a line B B′ perpendicular to both. Then

A B and D B′ will attract,
A B ,, B′ E ,, repel,
B C ,, B′ E ,, attract,
B C ,, D B′ ,, repel.

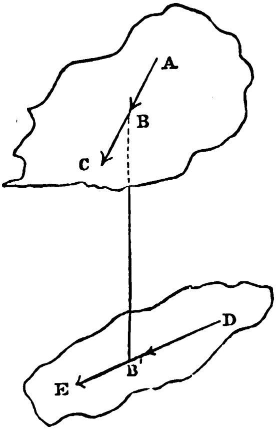


Fig. 206.

There will be an effort in A B C to swing round in the direction of the watch hands, and of D E to turn in the opposite direction, till they become parallel and in the same direction, all rotation will then cease, but direct attraction along BB′ will be at its greatest.

It follows from the last few paragraphs that currents which attract the same current attract one another, and also that currents which repel the same current attract one another. If two currents repel one another, the first must attract or repel if the second repels or attracts a third current. We may make also the same generalization in space as was made in Art. 261, in two dimensions, namely, to find whether two elementary currents attract or repel, continue their directions and draw the line from one to the other, which is perpendicular to both. If both currents flow from or both to this line there will be attraction; if one flows from and the other to, there will be repulsion.

264. Rectilinear Repulsion.—In Art. 262, the repulsion between A B and B E must continue when that repulsion has brought them into the same straight line, because when they are so they are not at an infinite distance apart. Again, we may look upon the attraction and repulsion of currents as resulting from the current-bearing wires being virtually a collection of elementary magnets at right angles to the current, all in one plane, and having their like poles all in one direction. Thus A will attract B, because the crossed ends of the elementary magnets of A are, fig. 207 (1), near the uncrossed of B. For the same reason C and B will repel. For the same reason *n s*, fig. 207 (2), will repel *n′ s′*. For the sum of the attractions *ns′* and *n′s* acting at a greater distance and obliquely, is not so great on the sum of the repulsions *n n′* and *s s′*. Accordingly, there is a tendency in the wire to divide by stretching. It must be admitted that neither of these explanations is quite satisfactory; but there appears to be little doubt of the fact.

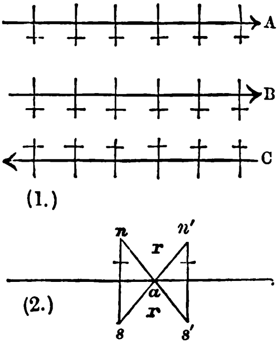


Fig. 207.

If one end A C, fig. 208, of a bent wire B A C is protected with gutta-percha so that only the end C is exposed, and balanced on D, while the end A C is in a cylinder E of mercury; then if D and the mercury are connected with a battery, the current passes down A C into the mercury, and the end A C rises out of the mercury. Or if, fig. 209, A B be a trough of mercury divided down the middle by a solid diaphragm E, and D C be a wire covered, except at its ends, and so bent in the middle that the bend clears the diaphragm as the wire floats on the mercury, then on introducing the poles of a battery, one into one division and one into the other, the wire moves away from the mercury which touches its ends.

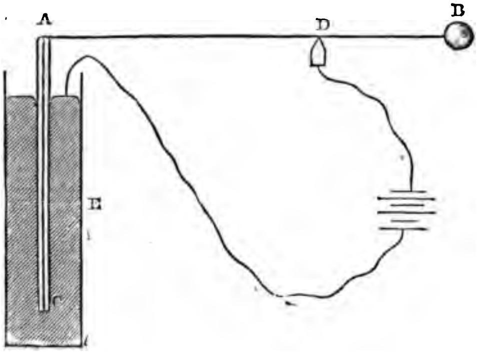


Fig. 208.

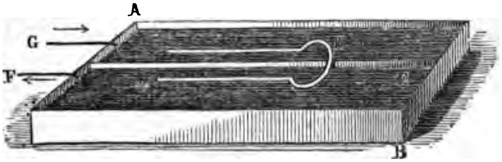


Fig. 209.

265. The attraction of currents moving in the same direction is well exhibited in the spiral automatic make and break. A spiral copper wire C is rigidly fastened above, and there connected with one pole of a battery. The other end of C just touches the mercury in a cup M, which is connected with the other pole of the battery. When the current passes, the elements of the current a_1, a_2, a_3, etc., are all in the same direction, and so attract one another. So do the elements b_1, b_2, b_3, etc. It is true that a_1, a_2, a_3, all repel b_1, b_2, b_3, but these repulsions act obliquely and at a greater distance than the attractions. The latter accordingly prevail, and the whole spiral contracts; the lower end is thereby lifted out of the mercury, and the current being thus broken the contraction ceases, the lower end touches the mercury, and so on.

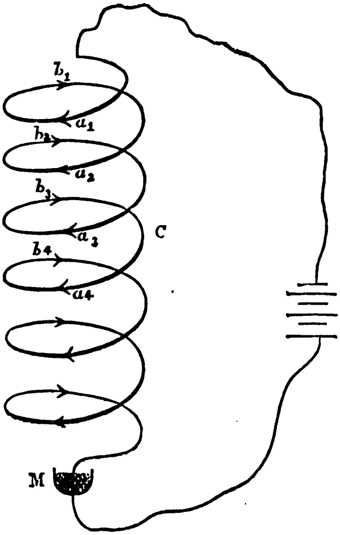


Fig. 210.

266. Circular and Spiral Currents.—Two currents in circular conductors may exercise attraction or repulsion according to the attitude of the circles towards one another. Thus, fig. 211 (1), the currents in A and B descend in front and ascend behind, they are always moving in the same direction, and consequently attract throughout. If B were placed on the other side of A, the direction of neither current would be altered, and attraction would be continued. But if (2) one (B) is turned round, the currents move in opposite directions throughout, and repulsion ensues; and this repulsion continues if B is placed on the other side of A. This change by turning one only of the circles through half a revolution is worth some further attention. Let us call the direction of motion of the hands of a watch, when we look at its face, positive. Set a wheel facing you to turn in the + direction; when you look at it from the other side it turns in the – direction. It has not altered its motion; but the ascending edge, along with everything else, which was *on your left* is now on your right, and *vice versâ*. If we, facing the north, hang up a circular hoop in a plane N.N.E., at such a distance that there is no apparent difference of thickness in its parts due to perspective, we cannot tell whether its plane is N.N.E. or N.N.W. So looking at the arms of a windmill in motion, in the twilight, or at such a distance that their attachment to the mill is obscure, we can, when the aspect is very oblique, easily imagine the arms to be turning in the opposite direction. We then fancy we are looking at the other side of the mill; so that if the sails are actually towards us in their descent, we fancy them away from us in their descent, which gives the notion of rotation in the opposite direction. This hallucination can, after a little practice, be as readily controlled by the will as can the introversion of a linear drawing representing a solid.

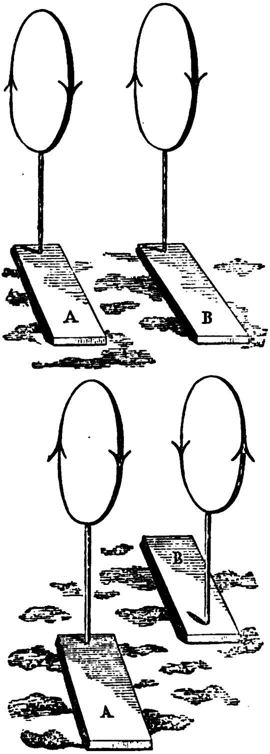


Fig. 211.

267. If we take two perfectly similar flat spirals A, B, fig. 212, traversed by currents in the same direction, and lifting up B we place it upon A, there is attraction. If we turn B over we cannot get the same perfect coincidence throughout. The turns of A and B cross one another at very acute angles if the spirals are slow. As the turns of B cross those of A at this acute angle, the currents moving in opposite directions repel one another. If A is also turned over, the attraction is restored. In fact, the two faces of both spirals act like the two ends of two bar magnets. This relationship is better seen if we consider the attitude of helices towards one another. Let the helices lie on the table. Then if the current traverses them, as indicated by the arrows, the letters *d* and *u* show whether the current is going upwards or downwards. It is clear that attraction takes place between coils whose sides nearest to each other are similarly lettered;

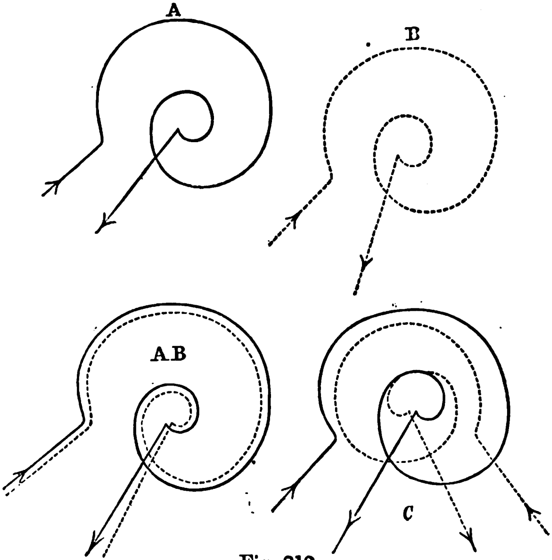


Fig. 212.

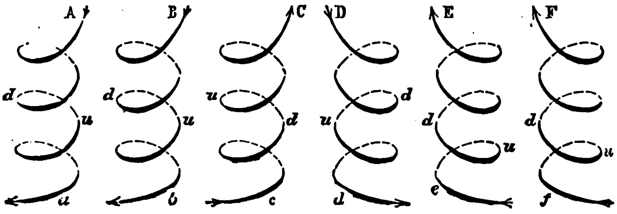


Fig. 213.

repulsion, when the reverse of this is the case. A B C are right handed, D E F are left handed spirals. In A B D the *current flows towards* us (the helices lying on the table), in C E F the current flows away. A and B are identical so are E and F. A is attracted by C and by D, and repelled by B and E (and F). B is of course circumstanced as A. The helix C is attracted by A (and B), and E (and F), and so on. If one of the helices is turned completely over (head to tail), the spiral is not altered in kind (Art. 227), but the direction of the current is altered, that is, if it flowed towards us before, as A, it now flows from us as C. It is clearly seen that given the helix A, which repels the similar helix B, when the direction of the current is changed, without altering the nature of the spiral, the repulsion is converted into attraction (C), also, the direction of the current being unchanged, when the nature of the spiral is altered, the repulsion is again converted into attraction (D). But when both are changed (E or F) the repulsion is maintained, the one reversal counteracts the other. All this has its close counterpart in electro-magnetization (Art. 227, 228), and the strength of the helix, like that of the electromagnet, is confirmed if we spin the insulated wire on a reel backwards and forwards in alternating left and right handed spirals. Also if A *a* be placed in the same straight line with B *b*, so that *a* is close to B, the current around *a* is in the same direction as that around B, and there is attraction. So also if *b* be placed on A. But if B *b* be turned upside down so that B is close to A, it is clear that the current circulates about the end A in the opposite direction to that in which it circulates about B, fig. 214. The end B therefore repels the end A. Similarly, the end *b* will repel the end *a*. The helices, therefore, have reciprocal polarity and have all the mutual relationships of magnets. We shall see in Chap. VII. how there has grown out of this strong analogy a theory of magnetism, which, if not true, is so truthful as to be of the greatest use in correlating facts.

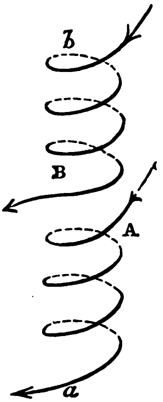


Fig. 214.

CHAPTER VIII.

MECHANICAL RELATION OF CURRENT TO MAGNET.

268. Current Reverser, Commutator, or Rheotrope.—We have had already frequent occasion to study the effect of reversing the direction in which a current is passing. Where such reversal has to be effected often and quickly, it is necessary to have some readier means than the disconnection from reversal and reconnection of the wires to the battery poles. The simplest form, and the one which illustrates best the principle upon which all rheotropes are constructed, is shown in fig. 215. Four troughs, *a b c d*, are dug out of a block of wood A, and the whole is varnished. The troughs are filled with mercury. Into two neighbouring troughs *b* and *d*, the electrodes from the battery are passed, and into the other two *a c*, pass the ends of the wire which has to complete the circuit. Two copper wires *e* and *f*, of which one is a little more arched than the other, can be placed either as in (1) where they are parallel to the sides of the block, or as in (2) where they are diagonal. The

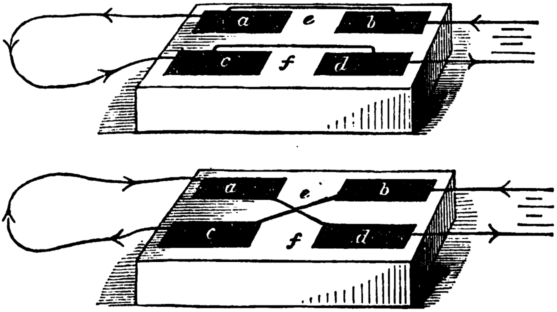


Fig. 215.

direction of the arrows in both figures shows how the current circulates. The current is instantly broken by removing either *e* or *f* in either case. In fig. 216, a more convenient form for rapid breaking or reversal is shown. A is a quadrant of a short circular cylinder hinged at its axis *a* on a stand B, and able to be turned by the handle C. Its two curved edges are covered with strips of sheet brass 1, 3, 2, 4, excepting in the middle where 1 is separated from 3, and 2 from 4, by ivory or ebonite or other non-conductors. 1 is joined to 4, and 2 to 3, however, by cross bands of brass which do not touch one another. Two springs of elastic brass rest on 1 and 2, and are fastened to two upright supports K and L. Two similar springs F and G are fastened to two similar supports. One pair of these supports (say K, L), receives the wires from the battery, the other M, N receives the ends of the circuit wire. In the condition of the figure, no current can pass, because F and G rest on the non-conductor. If C be depressed, 1 and 2 are brought under, and in contact with F and G, while D and E remain in contact with the same. Then the current passes from D to 1, to F, and so round to G 2 E. If C be lifted, 3 and 4 are brought under, and in contact with F and G, while D and E still remain in contact with 1 and 2. The current can then only pass from 1 across the transverse piece to 4, thence to G, and, having traversed the circuit in the opposite direction, it reaches F, crosses through the second transverse piece to 2 and E, and so to the zinc pole of the battery. Another form is seen in fig. 217. Two brass lobes A and B are separated by a zone of ebonite in which there is an axle.

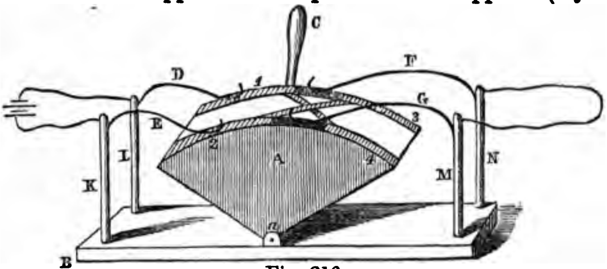


Fig. 216.

and which can be turned by the handle D. Forming one piece with A, is a circular brass arc having its centre at the axle. A similar arc is continuous with B. Upon these two rest elastic brass bands which are connected with the battery. E and F are also elastic bands rigidly fixed at G and H, and connected with the circuit wire. On turning D to the right, A is pressed against E, and B against F. When D is turned to the left, B is pressed against E, and A against F, and the direction of the current is obviously reversed.

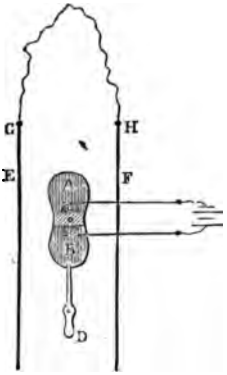


Fig. 217.

269. Attitude of Magnet to Current.—In Art. 107 was described the magnetization of a bar of steel by a spark discharge across it, and, in Art. 108, we saw how a current of electricity streaming from one of the conductors to the earth, through the manifold coils of a copper wire around an astatic pair of needles, turned them round. Further, in Art. 141, the motion was briefly considered of a magnetic needle, when stirred by a current running above or below from the north-seeking to south-seeking pole or the reverse. There also was described the temporary magnetization of a bar of soft iron when a current passes above or below, or from left to right or the reverse, athwart it; this latter effect being the fundamental experiment for electro-magnetism. And, Art 220, we have seen how the displacement of the magnetic needle out of its meridian is a measure of the strength of the current circulating around it. Lastly, in Chap. VI., use has been over and over again made of the astatic galvanometer, as a rheoscope at rest, in the same way as an ordinary balance is employed at rest for the determination of the equality of weights. We must now complete the examination of the mechanical relation between a current and a magnet, as a proper introduction to the electric relation between currents and currents, and also between currents and magnets, which will form the chief subject of the next chapter.

270. Fig. 218 will serve as a general diagram showing how a magnetic needle, free to turn only in a horizontal plane, is affected by a current running from end to end, above (*a* and *b*), below (*c* and *d*), from N to S (*b* and *c*), from S to N (*a* and *d*). Each case is in accordance with the universal rule, that, if we swim with the current, and in the current, and face the needle, the N.-seeking end of the needle turns to our left hand. This relation may be perhaps remembered as well by fancying a current always to pass down a straight wire in a right-handed helical path, and to suppose the current to have an influence similar to friction on the north-seeking magnetism only of the needle. Thus, in fig. 219, the parts of the spiral current away from the

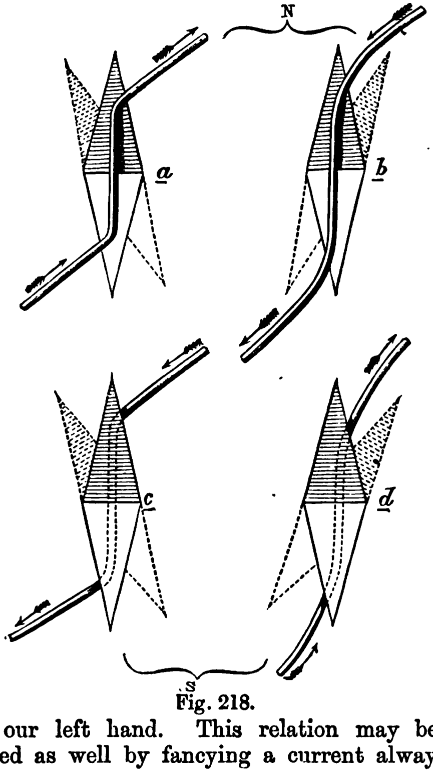


Fig. 218.

spectator are passing from right to left, and push the N.-seeking end of the needle in the same direction.

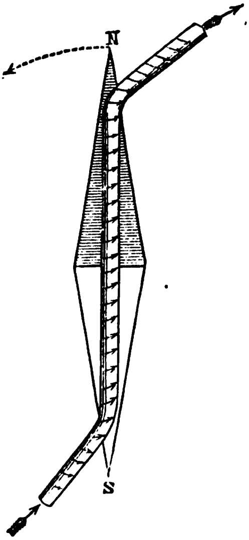


Fig. 219.

Since the needle turns one way when the current passes above it, and the opposite way when the current passes beneath, it follows that when the current is on a level with the needle, and running parallel with it, no deflection ensues.

271. Let now the current move vertically up or down while the needle, as before, can only turn in a horizontal plane, fig. 220. Applying either of the rules of Art. 270, the needle will swing round in the direction indicated by the arrows, and seek to set itself perpendicular to the plane of the paper, that is, while continuing at right angles to the current, it becomes also at right angles to the line which can be drawn from the centre of the needle perpendicular to the current. And, as before, a descending current at the S.-seeking end of the needle will produce the same motion as an ascending one at the N.-seeking end. This position can never be completely attained by a single needle on account of the directive magnetism of the earth. A fixed permanent magnet may, however, be so placed in the neighbourhood of, and above or below movable needles, so that the two have their like poles towards the same parts, that the directive magnetism of the *earth* is as nearly eliminated as we please.

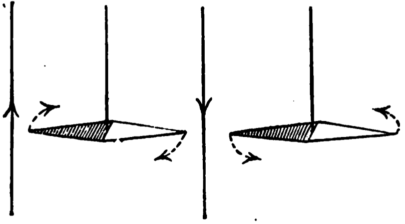


Fig. 220.

272. If the needle is, fig. 221, fastened to a horizontal axis in such a way that it can only turn in a vertical plane (that of the paper), a horizontal current passing from left to right in front of the needle, that is, between the spectator and the needle in a horizontal direction will also, by the previous rule, cause the needle to rotate in the direction of the watch hands. Indeed, we have here exactly the same condition as in fig. 218 (*b*). The three other variations of condition when the current passes from right to left, and when it passes behind the needle, need no special description.

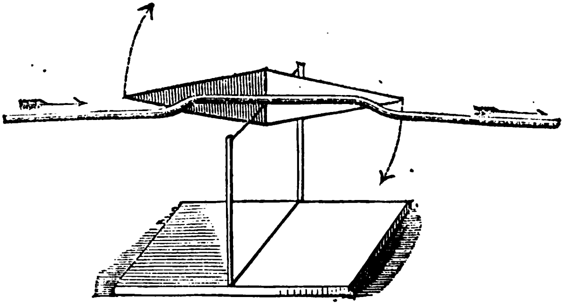


Fig. 221.

273. If the magnetic needle be not balanced upon its centre, but, fig. 222, is balanced on one end, say the S.-seeking, by means of a counterpoise *e*, so that it can turn in a horizontal plane, it will, when the current D descends in a vertical plane, that of the paper, turn in the direction of the arrow and take up a position, if it be astatic, at right angles to the line joining its N.-seeking end to the current, and which line is perpendicular to the current.

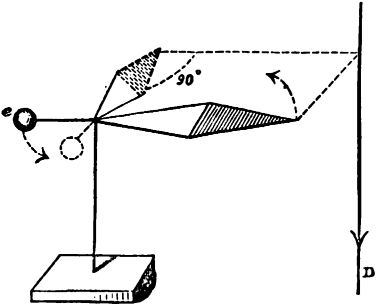


Fig. 222.

274. Strength of Force exerted by Current.—When a body swings or oscillates around a fixed point, whether as a pendulum by the force of gravitation, or like a disturbed needle by the directive magnetism of the earth, the force which acting on the disturbed body to bring it back is always proportional to the square of the number of oscillations which the body performs in a given time. If therefore a magnetic needle, when acted on by the earth's magnetism, only makes n oscillations in a minute, and when under the influence of another magnetic pole which, suppose, attracts the end of the magnet nearest to it, it makes the greater number m oscillations in a minute, then the increase is due to the new magnetic pole; and $m^2 - n^2$ represents the effect and is nearly proportional to the strength of the magnetic attraction between the surface pole and movable needle. In a similar way the force exerted by a current on a magnet can be determined by the alteration in the rate of the needle's oscillation which the current effects. Every force or influence which is not absorbed by the medium through which it passes, that is, whose energy only diminishes by dilution with space, must, when acting between two points, vary inversely as the square of the distance between them. This is approximately true, when the extension of the bodies influencing one another is inconsiderable in comparison with their distance apart. Accordingly, an indefinitely short current is found to obey this law when it acts upon a magnetic pole. But, if the current is indefinitely long, the action no longer varies inversely with the square, but inversely with the distance, that is, if the current be straight, inversely with the shortest distance between the pole and the current. If it be circular around the pole, then with the radius of the circle, and so on. Each element of a straight current makes a different angle with the straight line joining that element with the pole, and accordingly the various elements exert a different force upon the pole, that element being the most powerful which is at right angles to that line joining the pole to the current, which is at right angles with the current. This element with a straight current is also the one nearest to the pole. Two elements of the same, or different currents of the same strength, exert a force upon a magnetic pole in the ratio of *the sines* of the angles between their directions, and the lines joining them to that pole—greatest therefore when their directions are at right angles to that line.

The action on the magnet is also directly proportional to the current strength. ; In fact, we have estimated the current strength by pitting it against the constant directive magnetism of the earth in the tangent galvanometer, and this has been shown to be a trustworthy method by making comparisons with the Voltameter between the indications of the galvanometer and the quantity of electrolysis effected in a unit of time (compare Art. 224).

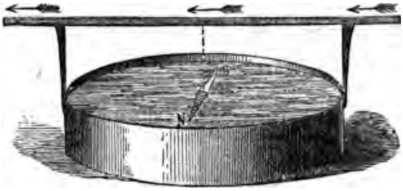


Fig. 223.

275. Remembering the polarity imparted to a bar of soft iron by a current passing across it, we can understand now, the behaviour of little bars of soft iron, such as iron filings, around a current. If a small permanent magnet be so buoyed as to float on water, a current in a horizontal current above the water will have two distinct effects. One will be to turn the needle at right angles to the current, and the other to make it move from whatever position it had until its centre comes vertically under the current. If a bar of soft iron be near the current so as to be magnetised, it will set itself as an electromagnet in the same attitude as the permanent magnet in the figure. That is, it will turn itself at right angles to the current and move so that that line joining its centre with the current, which is perpendicular to the current, is also perpendicular to

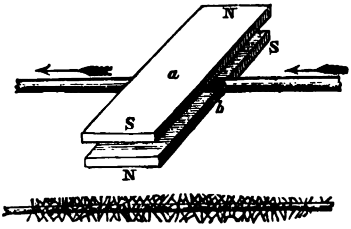


Fig. 224.

the bar. Two bars, such as *a* and *b*, fig. 224, when on opposite sides of the current, will become magnets having their unlike or attracting poles in the same direction. Attracting one another they will cling to the current wire. Iron filings accordingly cling to a copper wire through which a current is passing, and may be made to clothe it a quarter of an inch deep. The systematic arrangement of the particles of iron may be well seen on passing a current along a wire which is about $\frac{1}{8}$ of an inch above a sheet glass on which iron filings are strewn, fig. 225 (1) or (2), on making a hole in a sheet of glass, passing a current along a vertical wire which passes through the hole and strewing the filings on the glass. On tapping the glass the filings arrange themselves in concentric circles.

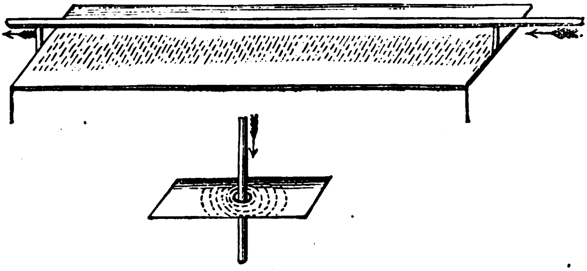


Fig. 225.

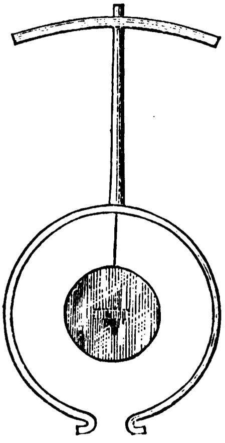


Fig. 226.

276. Reflecting Galvanometer.—The motion of the needle around which the current circulates has been used, Art. 220, as a measure of the current strength. For telegraphic purposes, where very feeble currents reach the recipient, the ordinary tangent galvanometer is modified in form as follows. The magnetic needle is very short. It is cemented on to the back of a very light glass reflector, and the two, which weigh only a few grains, are hung by silk fibre. Fastened above, on the box containing the needle and mirror and the brass band around which the current circulates, is an arched magnet, which can be lowered or raised and turned round so as to increase or diminish the sensitiveness of the suspended magnet. A pencil of light is focussed on to the mirror, which reflects it on to a paper scale. The deflexions of the needle are half those indicated by the travelling spot of light, supposing the scale to be circular.

277. Astatic Rheometer, or Rheoscope, or Galvanoscope. This has been already partially described in Art. 108. A piece of steel wire about an inch long has its two ends hardened. The wire is then uniformly magnetised and broken exactly in the middle. We get thus two magnets of exactly the same strength. These are fastened about an inch apart in the same plane to one another, and so that the N. of the one is in the same direction as the S. of the other. Two similar coils, each consisting of many hundred yards of fine silk covered copper wire, are placed side by side, about $\frac{1}{8}$ of an inch apart, their ends being fastened to four screws. The needles are hung by a fibre of cocoon silk, so that the lower is surrounded by the coils. The upper needle is above the coils, and immediately beneath it, and resting on the coils, is a circular disc graduated into degrees. The end of the upper needles are prolonged by pointers over this circular scale. The whole is covered with a glass shade, and is on a stand which can be levelled by screws. The coils ar

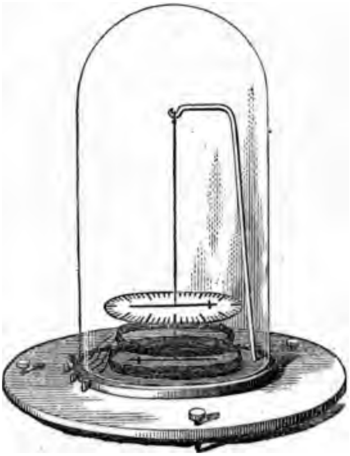


Fig. 227.

made in two pieces for the following purpose. If we wish to detect the existence of a single current, the two central terminals are joined together, so that we have then a continuous coil. If we want to measure the relative strengths of two currents, one is sent one way, round the one coil, while the other is sent the other way, round the other coil. The strongest will prevail and the needle will turn accordingly. A resistance introduced into the strongest circuit will equalise them, and from the amount of resistance introduced we can find the relative strengths of the currents. Used in this way, the astatic combination should remain at rest. The ordinary tangent galvanometer may be used in the same manner when, as mentioned in Art. 220, two currents may be passed round. It will be noticed that the current in passing between the two needles acts on the upper one, on account of its reversed polarity, so as to confirm the motion it imparts to the lower one in passing over it in the same direction, and under it in the opposite direction. The current as it passes beneath the lower needle of course acts on the upper needle at the same time, and with an effect opposed indeed, but less because of the greater distance. So if the current were brought back above the upper needle, there would be a further effect.

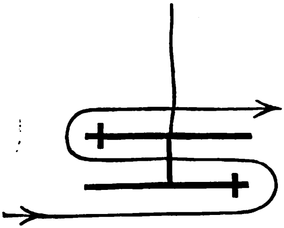


Fig. 228.

CHAPTER IX.

ELECTRICAL RELATION BETWEEN CURRENTS, AND CURRENTS AND MAGNETS.

278. Induced Currents, Secondary Currents.—In Art. 109 it was seen that when a spark discharge of frictional electricity was sent through a wire, a neighbouring closed circuit was simultaneously traversed by a discharge capable of leaping across a breach in the second circuit, and igniting gun-cotton, etc. Further, the secondary discharge so produced was itself able to cause a tertiary discharge in a third wire. We have to examine now the analogous phenomena with Voltaic electricity. A galvanometer G, having been tested to see what direction of motion of the needle corresponds to the passage of the electricity in at one terminal, is attached to a straight wire S. Another straight wire P can be fastened to the poles of a battery, and, by means of a rheotrope, the current in P can be started, stopped, or reversed. The following relations immediately declare themselves. When a current is started in P from left to right, the galvanometer needle turns in such a direction as to show that a current passes through S in the opposite direction. The current in P being continued from L to R, the current in S ceases. On stopping the current going in P from L to R, a current traverses S also from L to R, but immediately ceases. If the current be now started in P from R to L a momentary

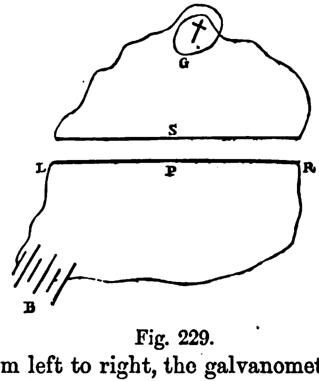


Fig. 229.

current from L to R passes along S. On stopping the P current from R to L, a current from R to L passes along S. So that, in general terms, the current in the secondary is in the opposite direction to that of the primary when the primary is started; when the primary is stopped the current in the secondary is in the same direction as that in which the current flowed before stoppage in the primary.

Let us now, having the primary wire at a considerable distance from the secondary, complete the circuit of the primary, so that the current in it is from L to R, and then advance the current-bearing primary towards, and parallel to, the secondary. As long as such approach is taking place, a continuous current in the secondary will be set up, and maintained from R to L, that is, in the opposite direction to the permanent current in the primary. When the approach ceases, the current in the secondary ceases. On withdrawing the L to R primary current, a current is established in the secondary also from L to R, and this secondary is continued as long as the withdrawing is continued.

The approach of the two, accordingly, produces the same effect as the establishment of the primary; the withdrawal of the primary produces the same effect as the stopping of the primary. And, indeed, we experience no difficulty in admitting that the total amount of electricity sent through the secondary, when a current of given strength is sent through the primary at a given distance from the secondary, is the same as would have been sent through the secondary if we had brought to that same distance from it from an infinite distance a current of the same strength in the primary.

Further, as we might anticipate, it is found that a permanent primary current, being in the neighbourhood of a secondary wire, when that primary is increased in strength, and when it is diminished in strength, the same effect is produced as when it is brought towards, and withdrawn from, the secondary respectively. In fact, increasing the current of the primary may be regarded as starting an additional current in the same direction.

279. Lenz's Law—Currents resist Motion.—It follows immediately from the above that when a current is near a conductor it resists motion. For, while moving the current towards the conductor, a current is moving in the latter in the opposite direction, and, therefore, there is repulsion between the primary and secondary. As long as we are moving the primary away from the secondary, a current is being generated in the secondary in the same direction as that in the primary, and, accordingly, there is attraction. So that, in either case, whether approach or removal is taking place, the motion causes such a current in the secondary as to resist that movement. We may compare this resistance to friction, it is essentially a responsive force. The chief applications of this law will be discussed further on, when we consider magnets as collections of currents.

As in the case of the frictional or high-tension electricity, the induced or secondary discharge could itself, in acting as a primary, give rise to a tertiary, and so on—so the induced current, from whatever cause arising (establishment, cessation, approach, withdrawal, increase, decrease), serves as a primary to a third wire. And, as in Art. 109, the effect depended upon the length of the wires in apposition, so here the wires should be as close together for as great a length as possible, this may be brought about by the wires being fashioned into flat spirals of isolated wire, one of which is placed on the other, or they may be employed as conaxial cylindrical helices. A primary will act upon a tertiary directly in the opposite sense to that in which it acts upon it by the intermediation of a secondary. Further, if we employ the other side of the secondary circuit to act on the tertiary, and so on, we get the primary causing circulation in all circuits in the same direction, and the condition becomes similar to that of a train of wheels driving one another, not directly, but by means of interposed wheels, fig. 230.

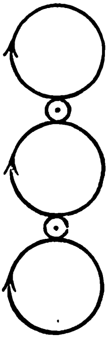


Fig. 230.

280. The Extra Current.—This term is rather inappropriate to the phenomena which it represents. An extra current is the momentary induced current, which is supposed to be formed in the primary itself at the moment of making or breaking, when the folds of the primary are situated towards one another like those of the primary to the secondary. Thus, imagine a wire A P B, fig. 231, to be folded as in the figure. A current started from A to B, in passing round P would cause a secondary or induced current S in the neighbouring part of the wire. This secondary moving in the same wire as the primary and in the opposite direction weakens it. But if the current from A to B be broken, the secondary current will try to move unquenched by the primary (because the primary has ceased). Accordingly, if we lay hold of the terminals of a battery, we do not feel nearly so great a shock as we do on separating the terminals after they have been in contact.

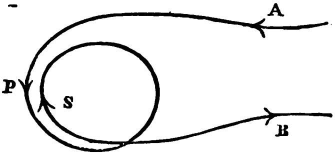


Fig. 231.

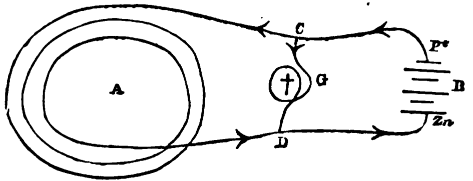


Fig. 232.

The existence of the extra current manifests itself in the following experiment:—Connect a battery B, fig. 232, a long spiral or helix A, and introduce a galvanometer G between the battery wires. The current from P*t* will divide at C, a part passing round the spiral A, and so reaching *Zn*, a part passing round the galvanometer G, and so causing a certain deflection. Let now the battery be disconnected at *Zn*. At the instant of disconnection, the needle of the galvanometer turns in the opposite direction to what it did before, showing that a current passes from D to C, and therefore passes through the coil A, in the same direction as the primary current; that is, the separate folds of this primary coil act as secondary wires to one another. An extra current is accordingly the secondary current in the primary wire. No doubt the extra current is formed on starting the primary, but, being then in the opposite direction to the primary, its *only manifestation* is to diminish the latter.

281. Strength of Induced Currents.—The strength of an induced current depends upon the strength of the inducing current, its nearness to the induced current, and the length of the apposed parts. The induced current, other things remaining the same, varies directly with the strength of the primary current, both when the latter is started or stopped. It varies also as the product of the lengths of the two currents. Accordingly, the strength of the induced current is much exalted, if its folds are many and parallel to the many folds of the primary.

282. Ampere's Theory.—Let a primary current circulate around P, as in fig. 233, in the direction of the watch hands, place S upon P, and at that instant a secondary current will pass round S in the opposite direction to the watch hands.

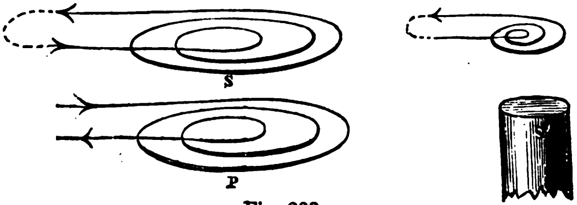


Fig. 233.

If the closed circuit S, instead of being placed upon P, is placed on the S′ pole of a permanent magnet, a current passes through S in the same direction as before. If the flat spiral S be taken away from an S′ pole of a permanent magnet, it becomes traversed by a current in the opposite direction. The S′ pole, therefore, behaves to the secondary precisely as a primary would do which is circulating in the direction of the watch hands. Placed upon a N. pole of a permanent magnet, a current traverses the secondary in the direction of the watch hands; taken off, the N. the current is reversed. Accordingly, the N. pole acts like currents circulating in the opposite direction to the hands of a watch.

The behaviour of the magnetic poles in instigating currents in neighbouring wires, and notably the alteration in the direction of the current which is brought about by change of the magnetic polarity alone, combined with the similarity in the mechanical action of a magnet on a current, and a current on a current, has given rise to the notion that magnetism is due to current circulation, a notion, of course, which receives great confirmation from the experience that current circulation can, and does cause, in neighbouring soft iron, a condition of the iron, as far as is known, quite identical with the induced magnetism it, when near a permanent magnet, receives, and, indeed, identical with the magnetism of a permanent magnet itself.

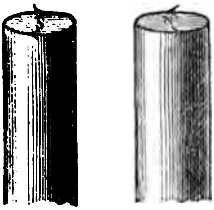


Fig. 234.

283. Imagine, in fact, a cylindrical bar of metal A B, and conceive currents to circulate around it in the direction of the arrows. Looking at the end *a*, we see the current circulating in the reverse direction to the watch hands; looking at *b*, we see them circulating in the watch hand direction. Regarding the bar A B (1), we see that the currents at A and B are moving in identical manner in regard to space. On turning the bar round from the aspect *a* to the aspect *b*, we have, in fact, reversed the direction of the current in regard to our own point of view in space, though not with regard to the bar itself, that is, the sequence of molecules which the current encounters in the bar.

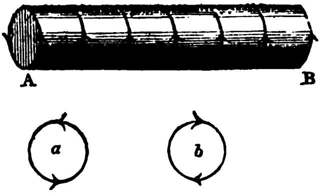


Fig. 235.

We may, indeed, conceive the circumferential current to be the residue or resultant of lesser, perhaps, molecular or atomic currents, whose internal careers neutralise one another. Fig. 236.

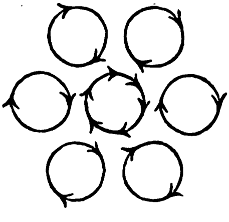
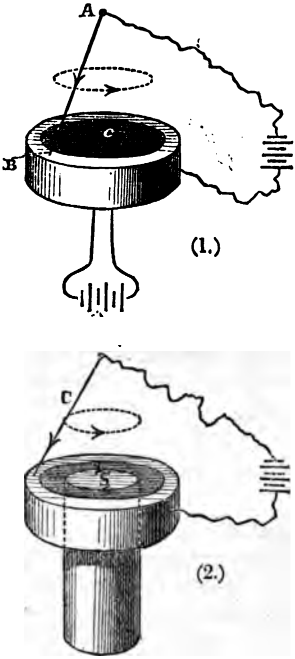


Fig. 236.

284. Magnets as Groups of Currents. — The mechanical actions of currents on currents which were considered in Chap. VIII., find their *close counterpart* in the mechanical action between currents and magnets; and a brief examination of the analogy gives the best justification of Ampère's hypothesis. In Art. 262 it was shown how a current approaching perpendicularly to an indefinite current would endeavour to slide along parallel to itself in the direction opposite to the fixed current's motion. Acccordingly, if, fig. 237 (1), a current A B pass down a wire hung at A into a circular mercurial trough which is in connection with the other pole of the battery; and if a current passes at the same time around a wire ring *c* inside the mercurial trough in the watch hands direction, the wire A B will describe a cone in the opposite direction, the end B moving through the mercury. If, fig. 237 (2), the wire *c* and its current be removed and replaced by the S. pole of a permanent magnet, exactly similar motion will ensue. Whereas, if the N. pole be used instead of the S., the motion of the wire will be the reverse. The motion of the rotation of the wire will be also in all cases reversed, if the current be sent upwards instead of downwards; for then, indeed, we have the condition of the current going from the indefinite current (compare Art. 262).



(1.)

(2.)

Fig. 237.

285. Let us for brevity call a circular current + when it moves round from our aspect in the direction of the hands of a watch, and − when in the opposite direction. Then the current around the S. pole when it faces us is +, that around the N. pole is −. Then the attraction between N and S, fig. 238, is due to the neighbouring and prevailing parts of the currents moving in the same direction. With like poles, N and N′, and S and S′, the neighbouring currents are moving in opposite directions, and there is, accordingly, repulsion. This attraction or repulsion extends along the whole length of two magnets put side by side, fig. 238, where

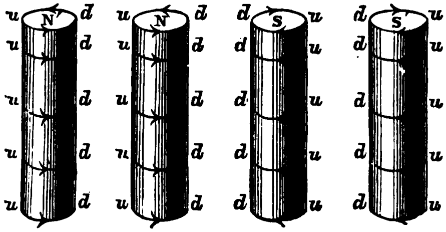


Fig. 238.

the letters *u* and *d* denote whether the current is emerging from or entering the plane of the paper. Notice here the entire similarity between this figure and fig. 213, Art. 267, where spiral currents alone acted on one another. Further, if (fig. 239) the unlike ends of two magnets are presented to one another, they attract, because their Ampèreian currents are parallel and in the same direction. Like poles repel, because their currents are in opposite directions.

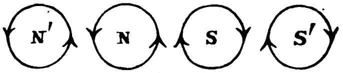


Fig. 239.

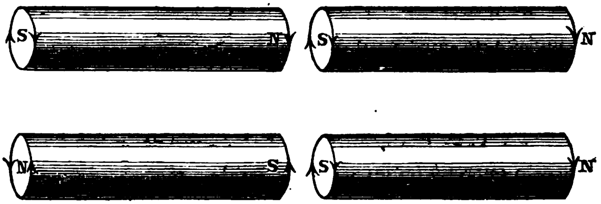


Fig. 240.

286. The fact of the production of a current through a ring or spiral wire, noticed in Art. 279, receives, therefore, the explanation that, on bringing the spiral down on the N. *pole, we* bring it down on to a current travelling in the –

direction, and, therefore, an induced current in the + direction moves round the wire. On taking it off the N., an induced current in the – direction traverses the wire. On bringing it on to the S., a current in the – direction is started: on taking it off the S., a + ly moving current is started. Of course, if a ring of wire placed on a pole receives a current in one direction, it will receive a current in the same direction with regard to space if it be turned over and then placed on the pole. But the current will be opposite in the sense of passing through the parts of the wire in opposite sequence. Thus, if a wire A B be placed on a S. pole, the direction of the current will be from A to B, as in fig. 241 (1). If the same wire be turned over and then put on the S, the current will move in the same absolute direction as before (2), and must therefore move from B′ to A′. If A and B are, therefore, connected with a galvanometer, the current through the galvanometer will be reverse when the wire is turned over. Thus a spiral *c* placed on a S. pole, will have a current through it from the centre to the circumference (1). Turned over and placed on the same pole, the current moves through the spiral from the circumference to the centre (2).

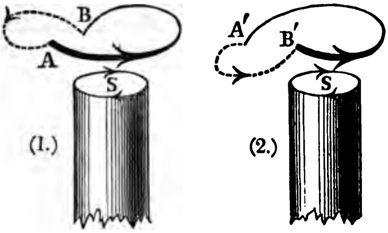


Fig. 241.

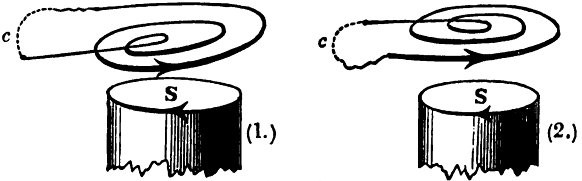


Fig. 242.

287. It is pretty clear that the total amount of approach on separation, and, consequently, the total amount of induced current must be the same, however the wire is moved, provided it always moves from a certain distance to a certain distance. We may jerk, slide, or twist the wire away, or employ any combination of these motions, and we always get the same amount of current, and this is the same in quantity as the current induced in the opposite direction when the wire is brought again, no matter how, into its original position. It is also clear that if a part of a closed circuit is brought between two unlike poles, these poles act in concert in producing an induced current, they also act in concert when the wire is withdrawn to cause a current in the opposite direction. Thus, the spiral C brought between N and S, fig. 243, which are represented sufficiently far apart to enable us to see the faces of both, the current will pass in the direction of the arrows by the joint action of the poles. It will pass in the opposite direction when the wire is withdrawn.

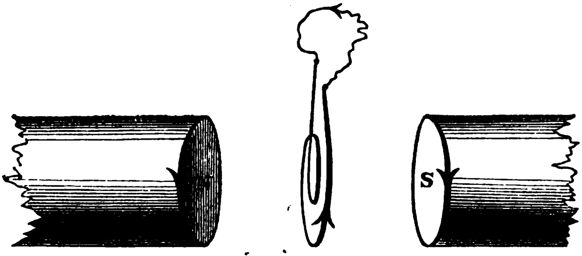


Fig. 243.

288. Instead of a flat spiral to lay on the magnetic pole, we may use with advantage a helical wire into which the magnetic pole is inserted. In bringing such a pole into a spiral or helix, the Ampèreian currents of the magnet at first all approach the convolutions, but when the end of the magnet has entered the helix it has to be moved away from the first convolutions, a differential action takes place; but the resulting current from first to last is represented by the final general propinquity. It is also apparent from fig. 244 (1) and (2), that if the S. end of a magnet is thrust into a right-handed spiral the current will pass down the spiral from *b* to *a*, and complete the circuit from *a* to *b* outside the spiral. The same pole thrust into a left-handed spiral (2) will cause the current to pass from *a* to *b* in the spiral, and from *b* to *a* outside it. On introducing the opposite or N. pole, the current will be reversed in both cases. The inversion of the kind of spiral produces a change, therefore, similar to that in Art. 283, resulting from the turning of the wire over. Of course, if the spiral is taken off and turned round, so that *b* and *a* change places, the direction of the current is reversed, the connecting wires outside the spiral are then crossed, and this latter change is the real analogue of that in Art. 283. On withdrawing a magnetic pole from the spiral the current is produced, in all instances, in the direction opposite to that which it followed when the pole was introduced.

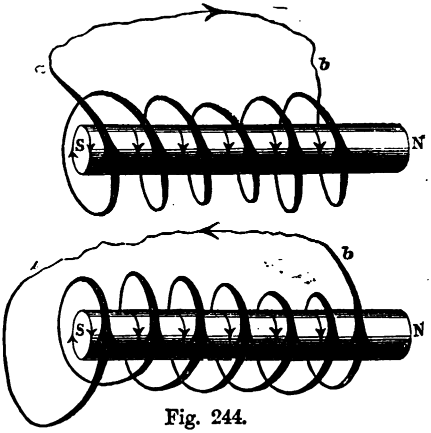


Fig. 244.

It will be noticed from the nature of the Ampèreian currents, namely, that they are all parallel to one another, that if the spiral be long enough to receive the magnets, the greatest effect will be produced by introducing the whole of the magnet, the N. end, say, following the S. into the helix.

289. From Art. 275 it appeared that the induced or secondary current was formed, not only by change of distance between the secondary wire and the already existing primary current, but also by the creation and destruction of the primary, and by its strengthening or weakening. Precisely analogous results are obtained if a bar of soft iron, resting in a magnet, be magnetised or demagnetised, or have its magnetism increased or diminished. Thus, fig. 245, a bar of soft iron, N′ S′

is in a right-handed spiral connected with a galvanometer. A magnet N S brought near to N′ S′ causes, as we shall see in Book III., similar polarity, that is, the poles induced in the soft iron are towards the same parts as those of the permanent magnet. The currents, therefore, of the electro-magnet will circulate as represented, at the N end. The currents in the wire will therefore follow, as in the figure. As N S approaches N′ S′ these currents will continue. On taking N S away, the magnetism in N′ S′ diminishes, and as long as this diminution continues the current is found to pass in the opposite direction.

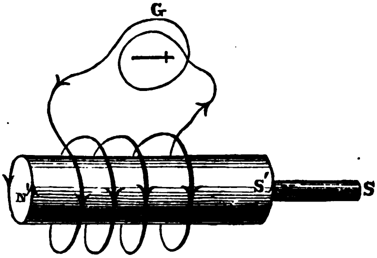


Fig. 245.

290. In Chap. V we examined the formation of an electro-magnet by a spiral current around a soft iron bar or core. A current passing down a right-handed spiral around a core causes the end of the core, which it leaves, to have N. polarity, and therefore the Ampèreian currents circulate in the electro-magnet, as shown in fig. 246, that is, parallel to and in the same direction as the exciting current. The Ampèreian currents, though thus caused by the current in the spiral, are not induced currents, for they go in the opposite direction to that which the induced current would pursue, and they are as permanent as the exciting current, while induced currents are momentary. We may imagine in a bar of soft iron that there are an infinite number of currents in an infinite number of planes, and that under the directing influence of the helix these arrange themselves parallel to the currents of the helix, and, therefore, parallel to one another, and in the same direction as the helical current, according to the rule examined in Art. 252. It follows that if we put

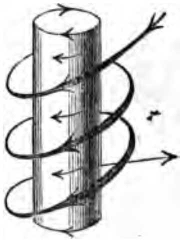


Fig. 246.

one helix inside another of the same kind, and put a bar of soft iron in the inner helix, and then pass a current round either one of the helices, the secondary current induced in the other helix will not only be brought about by the direct action of the first helix on the second, but also by the magnetism in the core, caused by the primary current reacting upon the second helix in the same direction as the primary acted. Thus, fig. 247, we suppose there are two right-handed helices *p* and *s*, of which *p* is inside *s*, and a soft iron core C is placed in *p*. When a current is sent down *p* from left to right, an induced current starts in *s* in the opposite direction. Further, the current *p* magnetises C, giving it the polarity in the figure. The Ampèreian current in C are in the same direction as that of *p*, and accordingly strengthen the secondary current by confirming the direct action of *p* upon it. On stopping *p*, again a current starts in the same direction as *p*, and the stopping of the Ampèreian currents in the electro-magnet assists the secondary. The core always assists the primary. And the joint effect is very much greater in inducing secondary than the effect of the primary alone. To this we shall return in Art. 294, and the following.

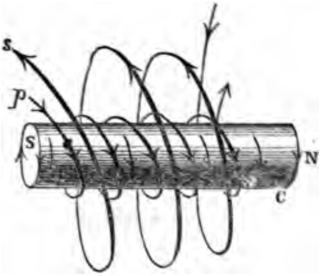


Fig. 247.

291. Solenoids.—In Art. 285, we examined the attractive and repellant properties of helices down which currents are passing, and showed that these helices had poles like those of a bar magnet. If, according to Ampère's theory, magnetism is due to systematic current direction, the above helices are to be regarded not only as similar to, but as actually being weak magnets. By bending the ends of a helix back into its cavity, carrying them along near the helix (not exactly in its axis), and bringing them out at about the middle, an arrangement is got which is called a solenoid, and which can be free to turn while a current is passing through it. Such an arrangement is seen in fig. 248. The solenoid is suspended by a fine thread *t*. One of its terminals *a* rests in a little mercury cup, and the other *b*, which is not quite central, moves in a circular mercurial trough around *a*. The cup and trough are connected with the poles of a battery. If the current ascends *a*, then A becomes S.-seeking, and B becomes N.-seeking, that is, A is repelled by the S.-seeking, or unmarked pole of a magnet, and attracted by the marked. B is repelled by the N.-seeking, or marked, and attracted by the S.-seeking or unmarked. Allowed to swing, the end B will point to the N. and A to the S. On reversing the current the solenoid swings round, its poles being reversed. The terminal wires of the solenoid may pass through a bung, and one of them may be armed with an amalgamated zinc, and the other with a copper plate. The whole is floated in acidulated water. In order that the directive magnetism of the earth may produce a sensible effect, the convolutions of the solenoid should be very numerous and close together. By properly balancing

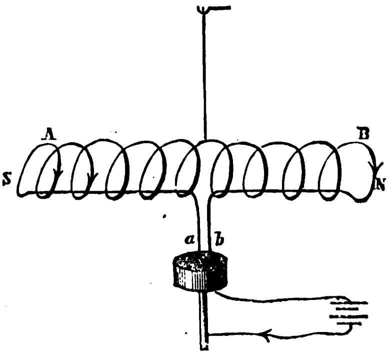


Fig. 248.

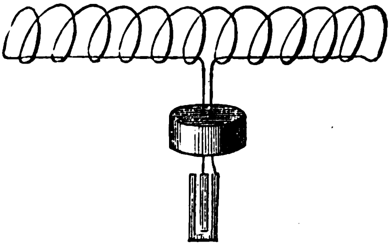


Fig. 249.

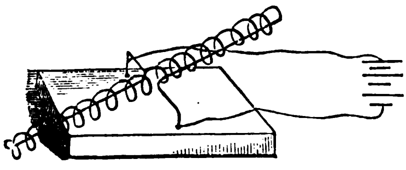


Fig. 250.

the solenoid horizontally, and on a horizontal axis, fig. 250, which may be done by bending its terminals, and resting them on two drops of mercury on a wooden stand, in such a way that the centre of gravity of the whole is a little below the line joining the ends of the terminals, then when a current passes, the solenoid dips like a needle.

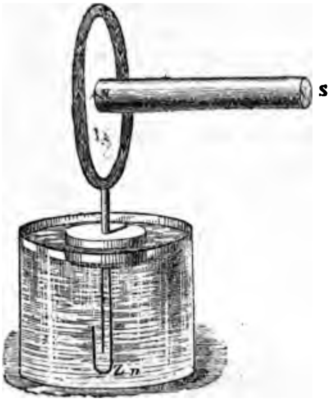


Fig. 251.

A few turns of insulated copper wire, fig. 251, in the form of a hoop shows the polarity remarkably well. The N. pole of a bar magnet presented to the hoop will attract it from a considerable distance. If the S. end be forced into the hoop, the latter will move off, and frequently it will turn round and impale itself on the magnet, running up as far as the middle.

292. The power enjoyed by magnets, either permanent or temporary, to call forth secondary currents, and the fact that those currents are always in the opposite direction to the Ampèreian currents when the latter are started, approached, or strengthened, gives rise to an application of Lenz's law, both curious and important, namely, the drag upon a moving magnet exercised by a neighbouring conductor, and the friction-like action between a moving conductor and a magnet at rest, which causes the latter to move.

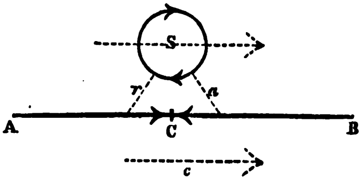


Fig. 252.

Suppose we move an endless conducting wire A B beneath the S. pole of a magnet which can turn in a horizontal plane. Let the conductor move from left to right, as *c*. Looking upon the part A C as a secondary, it is clear that a current will be established in it contrary to the nearest current of S, that is, from left to right. So that the current in S and the induced current in A C, being in opposite directions, will repel, and S will be pushed in the direction of *c*. Again, the part C B by the same motion, is removed from S. A current will therefore be established in it from B to C, which, being in the same direction as the neighbouring current of S, attracts S and drags it along. Pushed by the current in A C, and pulled by the current in B C, the pole S moves in the direction of the motion of A B, that is, from left to right; as though A B in its motion rubbed up against S. Similarly, if S were to move along in the direction A B, the current in A C would be in the same direction as the lower current of S, and between these there would be attraction or pull, while the current in B C would be in the opposite direction, and between S and B C there would be repulsion or push. The conductor A B would therefore tend to move in the same direction as the pole S. The N pole on the opposite side would behave in a similar manner.

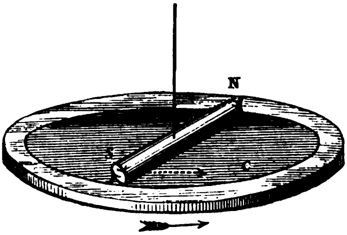


Fig. 253.

So that, fig. 253, if we place a magnetic needle N S on a pivot, and stand it on a sheet of glass to get rid of the influence of draughts, and turn beneath it a sheet of copper, or any metal C, the needle will follow the rotation of the copper. Or, inversely, if we support the disc beneath the magnet and spin the latter round, the disc will follow it.

Again, imagine, fig. 254, that we have two powerful electro-magnetic poles very near to one another, and hold between them a sheet of copper. The copper will move with extreme reluctance between the poles. The more violent the effort to move it, the more violent will be its resistance to motion. It will have no rebound, but its repugnance to motion will resemble that offered by a semi-solid to the passage of a knife. A spinning mass of copper will be quickly stopped when the neighbouring soft iron masses are magnetised. A thin copper ring dropped between the poles will fall as though through syrup. If the ring be broken the peculiar effect ceases, because no current can then circulate.

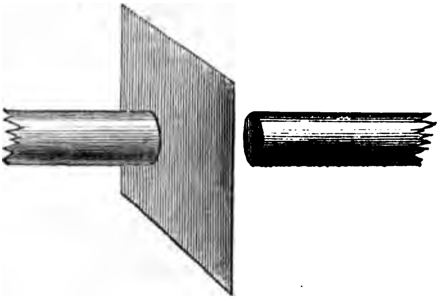


Fig. 254.

The over sensibility of the compass needle is corrected by placing it in a metallic ring; the motions of the poles near the metal cause currents in the metal, in all cases, in such directions as to oppose the motion. In fact, the law described in Art. 276 as Lenz's law, is here further illustrated.

293. Effect of Soft Iron Core in Primary.—In Art. 290 it appeared that the creation and cessation of magnetism in a soft iron core in the primary, assisted the direct action of the primary upon the secondary, in producing the secondary; and in Art. 289, the magnetization of a soft iron core, in a coil, was shown to produce the same effect as the introduction of a permanent magnet into the coil, and also the same effect as the starting of a current in the primary, in the same direction as the Ampèreian currents in the permanent or induced magnet. Accordingly, if a helix be wrapped round a mass of soft iron, and both be brought near the N. pole of a permanent magnet, a current is started in the wire which continues as long as there is approach. The current is reversed if the wire and iron is withdrawn, and the reversed current is continued if the wire and core is brought to the S. It is again reversed on withdrawal from the S., that is, withdrawal from the S. produces the same effect as approach to the N.

294. Magneto-electrical Machines.—All instruments for obtaining currents from magnets depend upon the principle in Art. 290 and preceding paragraphs. The crude form of such an instrument is shown in fig. 255. N and S are the north and south poles of a permanent magnet fastened in a vertical plane. Opposed to these poles, and as near to them as possible, are two soft iron cylinders A and B, connected away from the magnet by the piece C C. Around A and B is wound the wire *a b* in right-handed spirals. Let *a* and *b* be connected, and, by machinery which is not shown, let the system A B C be moved round in a vertical plane perpendicular to that of the magnet. Starting from the position in the figure, let B sink through the paper. A current will then move around B towards *b*; at the same time, a current starts around A from *a*. Accordingly, the removal of B from S, and A from N, both tend to send a current from *a* to *b*.

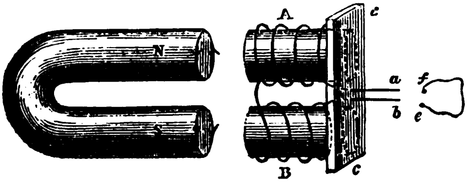


Fig. 255.

The approach of A to S, as the rotation is continued, produces the same direction of current as its removal from N. And the approach of B to N produces the same effect as its withdrawal from S. So that during the first half revolution the current passes from *a* to *b*. During the whole of the second half it passes, as is clear from exactly similar reasoning, from *b* to *a*. If we hold wires connected with *a* and *b* in the moist hands, we feel a succession of slight shocks as the induced current reverses its direction at each half revolution. If *a* and *b* are connected with a Voltameter, a mixture of oxygen and hydrogen is evolved at both poles. A thin platinum wire between *a* and *b* becomes red hot.

In order to get a continuous current in one direction between two other points *e* and *f*, say in the direction from *e* to *f*, we must introduce an rheotrope or current reverser, between the pair *a b* and the pair *e f*, in such a way that the *connection is* reversed at every half revolution; for then the connection being reversed when the current is reversed, the current between *e* and *f* will remain the same. This may be accomplished by splitting the metallic axis, upon which the system A B revolves, longitudinally, and filling the interstice with some non-conducting substance such as ebonite. If the terminals *a* and *b* are always connected with the same halves of the axis, and the points *e* and *f* are connected with springs which always press upon the same side of the axis, the above conditions are satisfied; for then at each half revolution, the spring connected, say with *e*, will change its connection from contact with *a* to contact with *b*, and this at the very moment that the current is reversed from *a* to *b* and becomes from *b* to *a*.

295. The magnetizable soft iron core and its surrounding wire are more advantageously applied to the permanent magnets in the arrangement known as Siemens' armature. This is shown in fig. 256. The armature resembles a shuttle C D, the wire is wound upon this. The terminals are connected with the parts *a b* of the split axle. Striding over the armature is a series of electro-magnets, of which only one is shown. These are flat, parallel, and very close together.

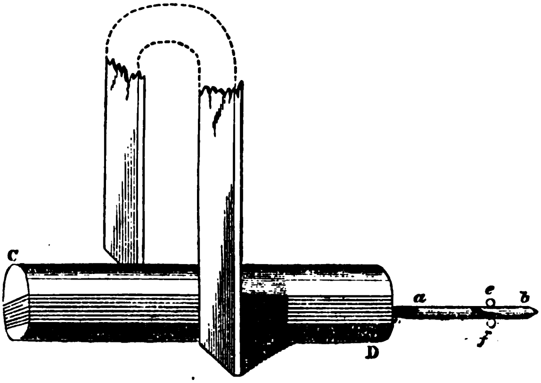


Fig. 256.

296. By employing electro-magnets instead of permanent steel magnets, a still greater effect may be produced. The current which excites the electro-magnet may be derived from a small machine such as just described. Thus, if we take a small machine, such as was described in 294, 295, and conduct its current around soft iron bars, replacing the magnets of 295, we get, on turning the armature of 295, a vastly increased current. The labour is of course greater. Instead of employing a separate system to generate the current, we may rely upon the existence of a little permanent or earth-induced magnetism of the soft iron itself. Thus the magnets of fig. 256 being replaced by soft iron, suppose that all of these are enveloped in wire, whose terminals are all connected with *a* and *b*. The slight magnetism in the soft iron masses will cause a weak current from *a* to *b*; part of this will pass from *e* to *f* at once, the rest will circulate around the soft iron masses, and by converting them into electro-magnets, will vastly increase the current of the armature, the effect and the cause are reciprocal; but both of course are dependent on the work expended on turning the machine. This resistance to motion is feeble at first, but soon increases as the magnetism rises and the current augments.

297. Induction Coils.—The electric current obtained by the above described magneto-electric machines is an induced or secondary current of which the primary is the group of Ampèreian currents circulating around the poles. The mechanical conditions of the genesis and extinction of this secondary, namely, the gradual manner in which the approach and withdrawal must be made, give also a continuousness to the secondary, and causes it to resemble the primary in kind. The sudden extinction of the primary, and the almost equally sudden demagnetization of the soft iron it envelopes: the sudden creation of the primary, and consequent sudden magnetization of the soft iron, cause the effect in the secondary to be concentrated in time, and so in a manner condensed. Shorter lived, but equal in total energy with the current produced on approach or removal, it acquires tension, and is converted under favourable conditions into frictional or high-tension electricity. In the ordinary medical coil, the secondary wire surrounds the primary, which again surrounds the soft iron core, consisting of a bundle of iron wires. An *automatic* make and break, similar to that described in Art.

236, is set in action by the passage of the current while the terminals of the secondary are held in the hands or applied to different parts of the body. The strength of the secondary is regulated by passing it to various distances over the primary. In the magneto-medical coil, the galvanic battery of the ordinary coil is replaced by a magneto-electric machine, such as that in Art. 294. The current generated in the wire surrounding the armature of a permanent magnet when the armature is turned before the magnetic poles, is the primary current, the other part of the instrument is similar to the ordinary medical coil.

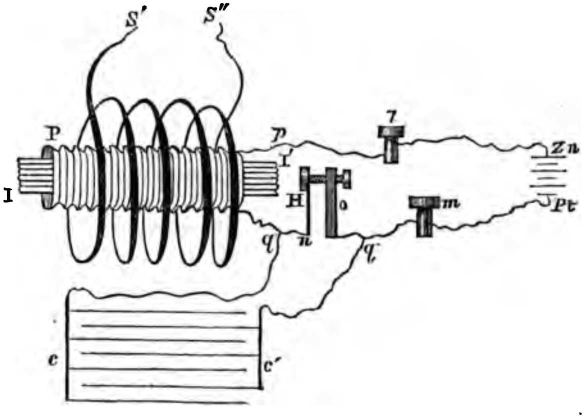


Fig. 257.

298. Ruhmkorff's Coil.—The principal of this is exactly that of the medical coil, with the addition of a "condenser" attached to the primary. The use of the condenser will be described immediately. Perhaps fig. 257 may serve to explain the principle of the coil. A bundle of soft iron wire I is enclosed in a coil P, passing several times backwards and forwards, of stout covered copper wire which may be ten or twelve yards long. One of the terminals *p* of this primary wire is connected by means of the binding screw *l* with one pole of the battery, of say 4 platino-zinc cells. The other terminal *q* of the primary is connected with the spring hammer H consisting of soft iron, which presses against the point of a screw working through the stand *o*, and so to the other battery pole. The primary terminal *q* is also connected with C, a series of sheets of tin-foil connected together along one edge, but separated by sheets of paraffined paper from a similar connected series C′, which are in connection with *q*′. The secondary wire, whose terminals are S′ and S″, consists of several miles of very thin silk-covered copper wire, wound in segments on an ebonite reel cylinder, fitting as close as possible over the primary. The passage of the current through the primary, when *l* and *m* are joined to the battery by magnetising the core I, attracts H from *o*, and so breaks contact, which is instantly restored in the manner described in Art.236. Let us suppose that both primary and secondary are simple single right-handed helices, and let the + current enter the primary by P*t*, *m*, *q*′. *o*, H, *n*, *q*, and so round to *p*, *l*, and *Zn*. On starting, the current in the primary acts directly on the secondary to produce a current from S′ to S″. The magnetization of I I′, which causes I to become N.-seeking also, sends the current from S′ to S″. On stopping the current in the primary, the current in the secondary moves both by the direct action of the stop of the primary, and by the demagnetization of the iron, in the opposite direction, that is from S″ to S′, and if the secondary current due to breaking and demagnetization were precisely equal in strength and identical in kind with that due to making the primary, and magnetising the core, we should have a current from S″ to S′ exactly equal and similar to that which passed from S′ to S″ on making the primary. But neither is the make-secondary identical in quantity nor kind with the break-secondary.

Referring to Art. 280, it appears that the extra current in the primary can, when the current is made, only manifest itself by diminishing the primary, which results, of course, in diminishing the secondary. On breaking the primary, the extra current, endeavouring to pass in the same direction as the broken primary, cannot do so through lack of path: it cannot, therefore, affect the secondary at all. Accordingly, the break-secondary must be stronger than the make-secondary *since the primary* in the latter case is diminished by the extra, in the former, not. When the primary is broken, if we can in any way store up the effort of the extra to pass in the opposite direction to the broken primary, if we can condense the extra current formed on breaking the primary, then, on making the primary, the direct effect of the primary on the secondary is augmented by the stored up break-extra, which, now escaping from its bondage in the opposite direction to that in which it entered, travels with, and fortifies the primary. The polarity of S′ and S″ depends, therefore, upon the fact that, on making, the primary is assisted by the stored up extra from the previous breaking, and diminished by its own extra which stores itself up. On breaking, the released extra acts in the same direction as the break of the primary, and, accordingly, the break-secondary is stronger than the make-secondary. The pole S″ becomes + towards S′.

The secondary caused by breaking the primary has, moreover, always a greater tension than that caused by making the primary: it is more completely transformed into static or frictional electricity. On employing a long and thin secondary wire, this transformation is complete. From S″ to S′ sparks leap across, having all the properties of those of a frictional or of a Holz's machine. These may be with a good machine eight inches in length, and since, if a spark passes at all, it passes at each break of the primary, a torrent of sparks may be obtained by the working of two or three cells of a battery.

299. The induction coil may serve to illustrate the resemblance of frictional and Voltaic electricity, not only by showing the genesis of the former from the latter, but also by giving an abundant source of the former kind, it enables us to trace a step further some analogies not quite sufficiently examined. In Art. 284, it was seen how a current, descending in front of one end of a bar magnet, rotated around that end in the direction opposite to the Ampèreian currents circulating around the pole. Precisely similar motion is observed in the spark discharge of the induction coil. In fig. 258, a hole is bored through a bar of soft iron M M, and filled with shell-lac, through which a wire is thrust in contact with a brass cap B, which is separated from the iron rod also by shell-lac. The outside of M is also thickly coated with shell-lac down to its centre G, which is a girdle of brass. The central wire and G can be connected with the poles of an induction coil, and when this is the case, sparks pass between the cap B and G. The lower half of M is encircled by a copper wire whose ends may be joined to a battery, thus causing M to become an electro-magnet. The upper half of M is surrounded with a glass globe, from which the air may be exhausted to any extent. It is found that as long as M remains unmagnetised, the spark between B and G follows a constant path. If M is magnetised, the spark glides round as it continues to strike between B and G. It glides in the opposite direction when either the polarity of the magnet is reversed, or the direction of the spark reversed. In fact, the phenomena of motion of Art. 258, where a current revolved about the magnet, can be here reproduced exactly with the spark discharge.

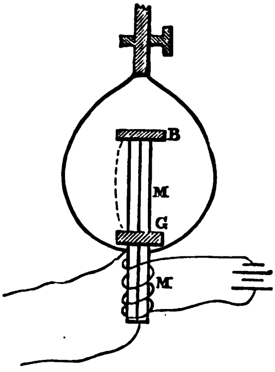


Fig. 258.

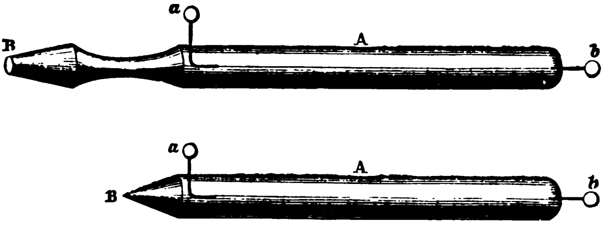


Fig. 259.

300. Phenomena of extreme beauty are exhibited when the spark from the induction coil is allowed to pass through glass tubes containing various gases in different degrees of rarefaction. The simplest form of such a vacuum tube is shown in fig. 259 (1) and (2). Two pieces of platinum wire, *a*, *b*, are fused into a glass tube A, which is drawn out at B. The air is exhausted from the open end by a good air-pump, and the glass is softened and drawn off at B. The length from *a* to *b* may be several feet, still, if the pressure left be only about $\frac{1}{8}$ inch, a luminous discharge takes place from *a* to *b*, when these two points are connected with the induction coil. The wire from which the spark enters the partial vacuum becomes armed with a brush-like discharge, the other wire becomes clothed with a layer of light. Vapours introduced into the tube before exhaustion have the power of inducing a remarkable stratification of the luminous discharge, and the colour is characteristic of the gas or vapour present. What is seen is, in fact, incandescent gaseous particles, and although up to a certain point the greater the rarefaction the longer is the discharge length, still, if the vacuum be as perfect as possible, such as may be got by the action of a mercury pump for several hours, or the chemical vacuum got by filling the exhausted tube with carbonic acid, and exhausting several times in the presence of dry caustic potash, which is afterwards fused, then the spark refuses to pass between wires only $\frac{1}{8}$ inch apart, while it will leap over an interval of 8 inches through ordinary air. On the other hand, if instead of rarefying the air, we compress it, we soon again reach a stage where the spark refuses to pass: where the insulation is perfect.

Beautiful as are the appearances presented by these vacuum tubes, at present so little is known concerning the *rationale* of the discharge through them, that we must not give more space to their description.

CHAPTER X.

RELATION OF THE CURRENT TO HEAT AND LIGHT.

301. Temperature affects Resistance.—The relation between heat and the galvanic current may be viewed from three positions:—(1), The influence of temperature on the resistance offered by bodies to the current; (2), the development of heat by the current; and (3), the generation of a current by heat. The effect of heat upon a metallic conductor is invariably to increase its resistance; but the alteration of resistance is so much affected by traces of foreign metals that the law connecting resistance with temperature is often masked. An iron wire, whose resistance at 21° C. was 690, had a resistance of 1660 at 285° C. At the brightest red heat its resistance was 4880. The resistance of a copper wire increased from 864 at 21° C. to 4700 at a bright red. A platinum wire, which at 21° C. had a resistance of 1985, had at a bright yellow the resistance of 6000. Within the range of temperature which can be accurately measured by other means, such as the air thermometer, it appears that the increase of resistance for every 1° C. is on the whole about 0·00366 of the entire resistance. This number is the co-efficient of expansion of gases for 1° C.; and the consequence of this coincidence is, that the resistance of the metal is proportional to its absolute temperature—*i.e.*, to its temperature above the absolute zero of temperature. But it must be remembered that this coincidence is only approximately true, and that an increase of temperature at a high temperature takes a different effect from the same increase at a lower one. Very careful experiments with a platinum wire 0·009 in. in diameter, showed (Siemens) the following amongst other results:—The resistance at 0° being taken as

100. Table (1) shows the resistance when the wire was heated in oil; (2), when heated in air:—

(1)		(2)	
0°	100·0	0°	100·0
60°	114·6	100°	125·0
110°	126·1	112·7°	128·7
160°	137·7	160·3°	140·4
210°	148·0	212·3°	152·9
260°	159·1	264·6°	165·4

302. The resistance pyrometer is based upon measurements such as the above. A platinum wire is coiled around an earthenware cylinder, and protected by an earthenware case. Balanced by a resistance bridge when cold against a similar coil or any other resistance, the protected coil is subjected to the source of heat, and the increased resistance measures the temperature. For exact measurements of this kind, where the instrument is calibrated with standards, we are not concerned with the source of the change. But it is clear that, apart from the specific alteration of conductivity due to heat, we have also the change in the dimension of the wire; it becomes longer and thicker. The co-efficient of expansion being ς, the length l, and the radius of section v for an increase t° of temperature, the length is increased $\varsigma\, l\, t$, and the sectional area, $\varsigma\, \pi\, v^2 t$.

The resistances of liquids which are decomposed by the current are diminished by increased temperature; and this diminution does not only depend upon the nature of the salt, but also on its degree of concentration. Thus, a solution of sulphate of copper resists according to the following table:—

	PER CENT. Cu. SO_4.					
	8	12	16	20	24	28
14°......	42·1	33·5	28·7	26·3	24·8	22·7
16°......	40·3	32·2	27·7	25·4	23·8	21·6
18°......	38·7	30·9	26·7	24·5	22·9	20·4
20°......	37·1	29·7	25·7	23·6	22·0	19·4
24°......	34·2	27·6	24·1	22·2	20·4	17·4
28°......	31·6	25·7	22·7	21·0	19·1	15·6
30°......	30·3	24·9	22·1	20·4	18·5	14·7

303. Melted metals, including mercury, follow the law of solids—namely, their resistance is increased on receiving heat. The resistance of a metal is greatly increased when, without change of temperature, it passes from the solid to the liquid state; at least this is the case in all of the few cases where such determinations have been made with accuracy.

Compound bodies behave quite differently from simple metals in their change of conductivity when their temperature is increased. And this is the case both with frictional and Voltaic electricities. Thus, if one end of a glass rod be heated red-hot, and placed on a charged electroscope, the electroscope is instantly discharged, if the hot part is touched with an earth-wire. On touching the cold part with an earth-wire no such discharge ensues. Two platinum wires, fused into the ends of a rod of glass about $\frac{1}{4}$ in. apart, and connected with a battery circuit in which a galvanometer is introduced, allow the current to pass between them if the glass is heated over a gas flame. More exact measurements can be made by putting mercury into a glass test-tube, and plunging the tube into a mercury bath, and connecting the interior mercury with the exterior by means of a circuit in which is a battery and a galvanometer. Thus, if the resistance of a certain thickness of glass at

	200° C.	is	2582
at	250	it is	158
,,	300	,,	17
,,	350	,,	12
,,	400	,,	8

The conductivities of simple binary compounds are differently affected by heat. Selenide of silver and selenide of copper behave like metals, that is, their resistances increase with the temperature, and they are not decomposed. Certain sulphides are in the same predicament; while others, such as the compound Cu_2S, undergo solid electrolysis. At 110° C. this body eliminates copper at the – battery polo, while CuS appears at the +.

304. Resistance affects Temperature.—The passage of a current through a homogeneous conductor is always accompanied by an evolution of heat, and the quantity of heat which is liberated in a given time is found by experiment to vary directly with the resistance, and directly with the square of the current's intensity (or quantity in a given time). Since the same quantity of current passes by any point of a circuit in the same time, it follows that, in a closed circuit, the heat developed in any one portion is proportional to the resistance of that portion. It is also obvious that, on increasing the resistance of one part of the circuit of a battery of given electro-motive force, we by no means proportionally increase the heat there developed, because the increase of resistance diminishes the current strength. The very heating of the part of the circuit where the resistance is greatest, diminishes the whole current strength and quantity. Accordingly, in establishing experimentally the relation between temperature or heat quantity on the one hand, and current quantity and resistance on the other, we must employ some means for measuring the current quantity which passes through the whole circuit, including the variable resistance. Perhaps the most trustworthy method of doing this is to introduce a Voltameter into the circuit, and to measure the heat quantity given off from a portion of the circuit, by determining the number of heat units given to a known weight of water in a given time, or by employing some other liquid to receive the heat, and by its expansion to betray its amount. Fig. 260, let S be a battery of three or four cells. A Voltameter, V, is placed in its circuit. The

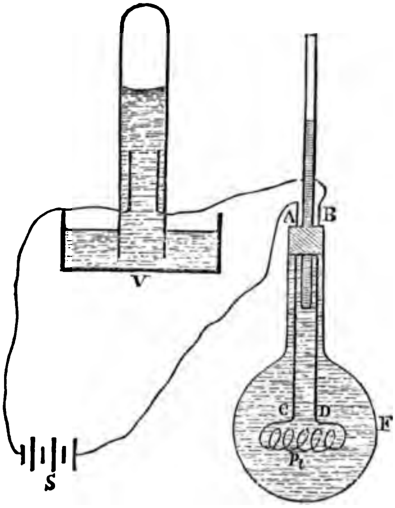


Fig. 260.

terminals A and B are connected with thick copper wires, A C and B D, which pass air-tight through the cork of the flask F, and are joined together at the ends by a spiral of thin platinum wire, P*t*. The flask F is filled with strong spirits of wine, which reaches up to a point on its graduated stem. Before use, the alcohol thermometer, which F forms, is calibrated. That is, the rise in the stem which corresponds to a given rise of temperature is noted by keeping F for an hour in water of known temperatures. From the known weight of alcohol in F, and its specific heat, it is easy to deduce the number of heat units corresponding to a given rise in level in the stem.

Calling H_1 the quantity of heat or number of heat units set free in F in a given time; N_1 the number of (say) cubic centimetres of detonating gas set free in V in that time, and R the resistance of P*t*. And calling H_2, N_2, R_2, the homologues of another experiment, then it is found that H_1 varies as $n_1^2v_1$, and H_2 as $n_2^2v_2$, or, generally,

$$\frac{H_1}{H_2}=\frac{N_1^2R_1}{N_2^2R_2}$$

This important law, known as Joule's law, is expressed at the beginning of this paragraph in words: the heat varies directly with the resistance, and directly with the square of the current strength. For the current quantity in a unit of time directly measures the current strength. We may put the above expression accordingly in the form

$$H \backsim S^2R;$$

and, since the resistance R varies directly with the specific resistance, sp_r, of the material, directly with the length l, and inversely with the section (s) of the conductor, $R \backsim \frac{sp_rl}{s}$, we have,

$$H \backsim \frac{S^2sp_rl}{s}.$$

If, therefore, we have one and the same current circulating around a mixed conductor, as is the invariable case with a battery circuit, S is the same in all parts; and the heat developed in any portion of the circuit is proportional to the resistance there encountered.

It is clear that the expression $H \propto S_2 R$ enables us to determine the resistance of a wire from the current strength S, and the heat developed in the wire; also to determine the current strength by observing the heat when the resistance is known.

305. — Several experimental illustrations of the consequence of Joule's law are of interest. If, for instance, a wire made up of alternate pieces of platinum and silver wire of the same thickness serves to conduct a strong current, the same quantity (S) of electricity passes through each portion. The resistance of the platinum being greater than that of the silver, the former is heated most, and may become red-hot while the silver remains cool enough to be handled. Again, if a current passing along a platinum wire is just sufficient to bring it to incandescence, and if we heat a portion of the wire, the resistance of that part is increased (Art. 301), the current strength is diminished, and the remainder of the wire ceases to glow, because it no longer has to convey so much electricity. If the current be just insufficient to make the wire glow, and we cool a portion of the wire by plunging it into water, the whole wire offers less resistance, the current strength is thereby increased, and the increased current, passing along the uncooled part, heats it to incandescence, and even to fusion. It is for a similar reason that a wire may glow and melt if it is very much shortened. Let us suppose that the resistance of the wire we employ is incomparably greater than all the rest of the resistance, so that we may consider the current strength to be inversely proportional to the wire length. A long thin platinum wire interposed in the circuit offers great resistance. The heat in that wire is proportional to the length of the wire multiplied by the square of the current. If we halve the length of the wire, and at the same time keep the current the same, we halve the heat developed in the wire, because we halve its resistance. But we do not halve its temperature, because, while the heat is halved, the matter is halved. On halving the length of the wire we, however, by halving the resistance, double the current; and since the heat varies with the square of the current, we must have an increased quantity of heat on a shortened wire; for both reasons, then, the temperature rises.

The temperature of the platinum wire is of course by no means a measure of the amount of heat it is giving off. The cooling effects of the medium, even of gaseous media, is variable; and the greater the cooling effect, the less on the one hand is the resistance, and the greater on the other is the current strength. The heat developed can best, in comparative experiments of this kind, be deduced from the current strength as shown by the chemical work done in the Voltameter. Thus, if a Voltameter and a resistance wire both form parts of the circuit of a battery, the wire may be surrounded by different gases which will have different cooling effects on the wire, and exhibit different current quantities in the product of the Voltameter. Thus, if in a given time 77 cubic centimeters of detonating gas are formed, when the resistance wire is surrounded by hydrogen, only 65 are given off when oxygen is used, 64 with nitrogen, and 63 with air. If the air surrounding a wire which is just beginning to glow be rarefied, the wire glows brightly. Its heat can no longer be carried off by convection and conduction, but escapes by radiation alone.

306. The heat developed in liquid conductors also follows Joule's law. The conduction of electricity through liquids which are not metals, is universally accompanied by electrolysis, and the products of electrolysis, if gaseous, escape with a large quantity of the heat due to resistance, or the electrolytes in many cases react upon the liquid. It is in some cases possible after the passage of the current to find how much of such secondary action has taken place, and thus from data derived from independent experiment to make proper correction on the observed heat liberation. But it is most satisfactory so to arrange the experiment that after its conclusion no new bodies shall be present. If we take, for example, a solution of dilute sulphuric acid and electrolyse it between platinum electrodes, the central portion of the liquid will become the warmest, that around the O pole less warm, and that around the H pole least warm of all. This is owing to the carrying off of the heat by the gases. If, however, we electrolyse sulphate of copper between copper poles, copper is deposited on one pole and dissolved from the other, and those take place in exactly equal quantities. The effect of all secondary change is therefore eliminated, and the heat quantity as derived from the rise in temperature, the mass and specific heat of the sulphate of copper solution is found to be proportional to the resistance and the square of the current strength.

Since, then, the heat of the liquid conductor and the heat of the external conductor of a battery or cell both follow the same rules, the total heat of a battery varies as the total resistance multiplied by the square of the current or

$$H \backsim S^2R \text{ and since } S = \frac{E}{R}$$

when E is the electro-motive force,

$$H \backsim \frac{E^2}{R}$$

$$\text{and } H \backsim E\,S.$$

If, therefore, the electro-motive force remains constant, the heat developed is proportional to the current. Now, if the electro-motive force is the same, the current is proportional to the quantity of chemical action which takes place in the battery; *i.e.*, to the amount of zinc dissolved. Accordingly, for the same electro-motive force, the heat developed in the whole circuit is proportional to the amount of zinc dissolved. This may be experimentally proved by connecting a pure zinc and platinum plate by means of a platinum wire under water containing sulphuric acid. After a fixed time the temperature of the whole is found to be raised to an amount proportional to the weight of the zinc dissolved. Experiment further shows that the quantity of heat thus developed throughout the circuit, when the zinc of a couple dissolves, is exactly the same as the heat which would be developed if the same quantity of zinc dissolved in the acid alone. The effect of the galvanic coupling is accordingly neither to increase or diminish the quantity of heat set free on the solution of the zinc, but to distribute that heat throughout a conductor of unlimited length.

307. Thermo-electricity.—Currents caused by heat. If we fasten, by means of wires of any kind, a copper wire to one galvanometer pole, and an iron wire to the other, and bringing the two into contact with one another gently heat the place where they touch, the needle of the galvanometer turns and shows that a current passes through the point of contact from the copper to the iron. If we drop a little ether on the place of contact so as, by evaporation, to cool it, a current passes round the galvanometer in the opposite direction, that is, through the point of contact from the iron to the copper. On the further study of this fundamental experiment, it is found that whenever two pieces of unlike metal are heated together, and the parts not heated are joined, a current passes through the whole circuit. The direction which this current takes is always reversed if, instead of being heated, the place of contact of the two is cooled. Yet, owing to the very great influence which impurities in the metals exercise and the effect of internal strain in them, the position of the metals in the order of thermo-electric tension is rather uncertain in several instances. In the following table the metals are arranged in such an order, that on heating the point of contact of any pair, the current passes through the point of contact from the one above to the one below. Fig. 261.

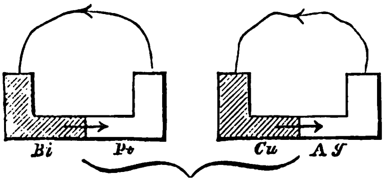


Fig. 261.

1. Bismuth.
2. Nickel.
3. Cobalt.
4. Palladium.
5. Platinum (1).
6. Uranium.
7. Copper.
8. Manganese.
9. Titanium.
10. Mercury.
11. Lead.
12. Tin.
13. Platinum (2).
14. Chromium.
15. Molybdenum.
16. Rhodium.
17. Iridium.
18. Gold.
19. Silver.
20. Zinc.
21. Tungsten.
22. Platinum (3).
23. Cadmium.
24. Steel.
25. Iron.
26. Arsenic.
27. Antimony.
28. Tellurium.

It is usual to consider the bismuth the most + and the tellurium the most − metal of such a list, so that when the joint of the two is heated, the bismuth becomes the − pole and the tellurium the +. Compare figs. 262.

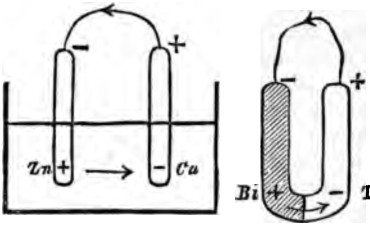


Fig. 262.

The condition of aggregation in affecting the position of a metal on the list, is seen in the case of platinum, where the varieties of platinum are cast, rolled, and drawn respectively. The mixture or alloys of the above metals by no means occupy places intermediate between those of their constituents; on the contrary, a mixture of 12 of bismuth and 1 of tin by weight, is below antimony on the scale. The lowest on the scale of all mixtures of bismuth and tin is the one consisting of nearly 15 of bismuth to 1 of tin. A greater proportion of bismuth brings the alloy towards bismuth. Bismuth and zinc alloys are all situated between bismuth and zinc. Zinc and tin are all between zinc and tin. Zinc and mercury are all between the two constituent metals. Bismuth and lead, tin and lead, antimony and bismuth, antimony and zinc have all special ratios with which the thermo-tension of one of the constituents is exceeded. These ratios are generally distinct atomic ratios.

308. Concerning the strength of such thermo-electric currents, several determinations have been made. The electro-motive force of various couples, when their ends are kept at a fixed difference of temperature, have been compared with the electro-motive forces of various galvanic couples. A bismuth-copper couple having a difference of temperature of 100°C., has the electro-motive force equal to 0·015 of a Daniell's cell. A copper-German silver couple of 100°C. temperature difference, has an electro-motive force of 0·00011 of a Daniell; an iron-German silver couple has, with a difference of 15°, an electro-motive force of 0·00015 of a Daniell, For one and the same couple, the electro-motive force is found within certain limits to be directly proportional to the temperature difference. The limits of temperature within which this is true is different for different couples. With a platinum and palladium couple the regularity holds good from 0 to 350°C. In almost all other cases the electro-motive force diminishes for the same temperature difference as the temperature rises.

In very many cases this diminution of the effect at increased temperatures results in its extinction at a certain temperature, and a reversal at higher ones. The experiments in this direction are not in good accord with one another. A zinc-silver element, of which one end is held at 0°, develops the strongest current when the other end is at 120°C., at higher temperatures it diminishes until at 225°C. it becomes nothing; at higher temperatures the current passes the other way. With zinc-gold the maximum is at 70°, the zero at 150°. In another series of experiments, the following results were obtained:—

Couple.	Maximum.	Reversal.
Zinc-iron,	143°	252
Tin-iron,	167°	...
Copper-iron,	169°	270
Silver-iron,	184°	295
Gold-iron,	195°	...
Brass,	206°	...
Lead-iron,	235°	...
Zinc-silver,	...	155
Zinc-copper,	...	171
Gold-brass,	...	224

309. The Thermopile.—Small as is the electro-motive force of a thermo-couple, its constancy when the temperature difference is the same, and each temperature is the same, makes it a valuable instrument for confirming electro-dynamic laws; and, in the form of a battery or pile, it becomes, connected with the astatic galvanometer, a sensitive thermoscope and thermometer. If a series of bars of bismuth and antimony are soldered together at alternate ends, as in fig. 263, and the terminal bismuth connected with the terminal antimony, the current will pass in the direction of the arrows when the lower half is warmer than the upper. The electromotive forces at the several junctures are additive like those of a battery linked tandem. The form of fig. 264 is that generally given to the thermopile. Square bars of bismuth and antimony are arranged side by side, so that their faces are situated like the black and white squares on a chess-board. The alternate ones at both ends are soldered together as in fig. 264. The terminals are brought down to binding screws on the stand, and the faces of the pile are provided, for radiant heat experiments, with reflecting hoods. Such a thermopile, joined to an astatic galvanometer, shows the slightest difference of temperature at its two faces. Even the heat of the human body at several yards distance will be indicated. Used as a thermometer, a constant source of heat is placed at a known distance from one face; and the source of heat which is being tested is placed at such a distance from the other face that the needle is at rest. The intensities of the known and unknown sources are then inversely as the squares of their distances from the respective faces of the pile.

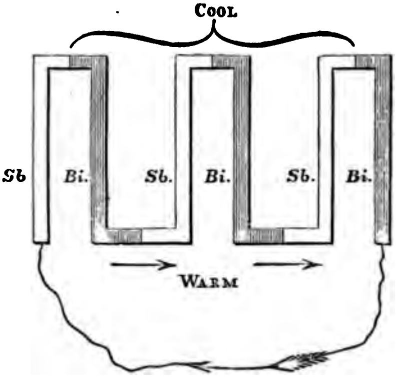


Fig. 263.

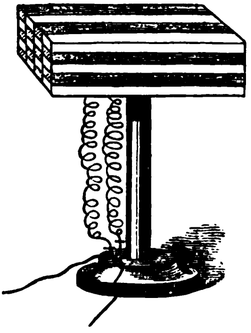


Fig. 264.

310. In the above pile it was mentioned that the bars were soldered together. Here we have, therefore, a contact, not between bismuth and antimony, but between bismuth and solder, and solder and antimony. It is found experimentally that when any number of metals are joined together in sequence, and the whole of the joints be equally heated or cooled, no current will pass. Thus, let the copper wire, fig. 265, which encircles the galvanometer, be joined to zinc, iron, tin, and silver in succession, which last is joined to the copper. If all joints are heated equally no current passes. Now, we know that, on heating the CuZn joint, a current passes through this joint from Cu to Zn. Accordingly, this current must be neutralised by the joint action of the CuAg, the AgSn, the SnFe, and the FeZn. If the joint, CuZn, is heated and all the rest are cooled, just the same current passes as when CuZn is heated, and the other Cu being brought to the other end of Zn, the junction there is cooled.

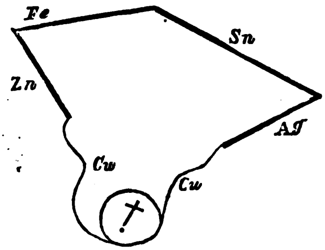


Fig. 265.

The thermo-current is excited not only between unlike metals, but also between parts of the same metal at different temperatures. In this respect silver, copper, and tin are differently circumstanced from almost all other metals. For if silver, copper, or tin, at 100° C. be laid upon the same metals at 8°, a current passes in each case from the cold to the hot metal. With zinc, platinum, gold, cadmium, and brass the current passes from the hotter to the colder metal. The same is true with silver if the temperature difference be greater—namely, if the hot metal be 250° and the cold 8° C. With mercury no current passes under any circumstances. The direction of the current seems, however, to be considerably influenced by the purity of the surface. Speaking generally, we may say that, with pure surfaces, the current generally passes from the warm to the cold; with oxidised or carbonised surfaces the direction is often, though not always, reversed.

Between metals of the same chemical nature, but of different degrees of hardness, currents also pass when the point of discontinuity is heated. With steel hardened by quick cooling, the current passes through the heated joint from the hardened to the unhardened. With brass the current passes in the opposite direction.

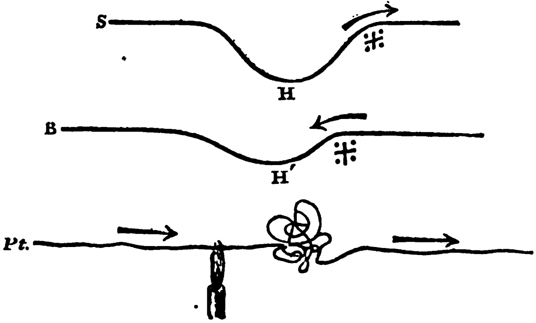


Fig. 266.

If a part of a thin platinum wire be tangled together into a manifold knot, and the wire near one side of the tangle be heated, a current passes towards the tangle, and this however thoroughly the wire is annealed.

311. Thermo-currents with Liquids.—The examination of thermo-currents between liquids is attended with some experimental difficulty and uncertainty. The most trustworthy experiments have been made in an apparatus shown in fig. 267. A cylindrical wooden vessel, V, carries below two tubes, which are closed at the bottom by two caps of the same metal. The two tubes are partially filled with the same liquid, L_2, and some lighter liquid, L_1, fills the remainder of the tubes and part of the vessel, V. Around the junction of the liquids in one of the tubes is a metal casing, through which steam can circulate. The moment it does so, the galvanometer, G, which is connected with the metal caps, is deflected. To avoid currents, caused by heating the liquid in contact with the caps, the ends of the tubes are immersed in cold water. It is found that the electro-motive force is nearly proportional to the temperature difference of the two surfaces of contact. Further, that if L_1 be the same as L_2, only more dilute, the current passes always from the weaker to the stronger solution; and the greater the difference of strength, the greater is the electro-motive force. When solutions are used of different metals of the same strength, that is, containing in the same volumes quantities of metals in the ratio of their equivalents, it appears that the order of tension of the solutions is the same as that of the metals themselves.

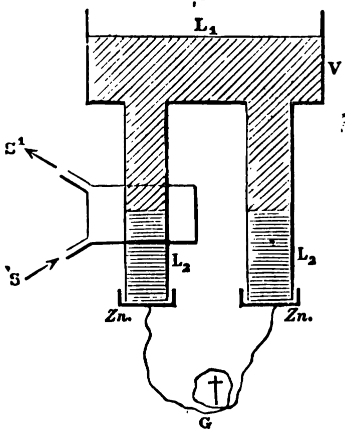


Fig. 267.

312. Heating and Cooling of Joints by the Current.—We have seen that, when the juncture between bismuth and antimony is heated, the other and cooler ends being connected, a current passes through the joint from bismuth to antimony (1). It almost follows, as a matter of course, that if (2) a current is sent from a battery through the joint in the same direction, the joint will be cooled; for if the supply of heat to the joint sends the current in one direction, the motion of the current in that direction demands heat at the joint. This demand for heat is exhibited by the coldness of the joint. In the same way, since the withdrawal of heat from the joint, the cooling of the joint sends a current through it from the antimony to the bismuth, a current (3) from the antimony to the bismuth through the joint will throw out heat from the joint. The joint gets warm. The experiment can be easily shown by sending a current, as in (3), from a single cell from the bismuth to the antimony, and then disconnecting quickly from the cell, and connecting with a galvanometer. The motion of the needle shows that the joint is hot. The faces of two thermopiles pressed together, but separated by a film of collodion, may be conveniently used for such experiments. The one pile is connected with a galvanometer, the other with a rheotrope connected with a cell. A little hole being bored in the joint of a single BiSb couple, and filled with water, the latter may be frozen when the current passes from the bismuth to the antimony. It has been proved experimentally that the heating and cooling effects are directly proportional to the current strengths. The above-described effect is known as the Peltier effect; it can scarcely be said to have been extended to liquid couples.

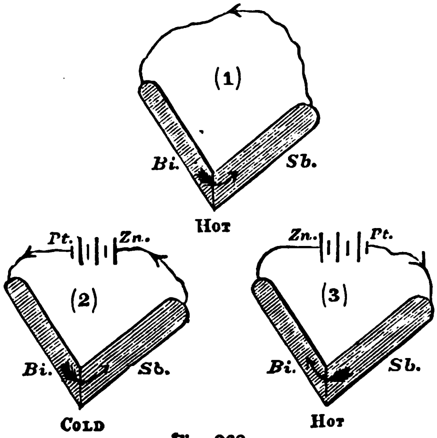


Fig. 268.

313. Effect of Light on Resistance.—There is at present only one satisfactorily established case in which light affects conductivity. A bar of crystallised selenium and a reflecting galvanometer of great resistance being introduced into a circuit of two Daniell's cells, bring the spot of light to a point, which may be considered as zero, when the selenium is in the dark. On exposure to diffused daylight or to artificial bright light, the resistance of the selenium is instantly diminished. On darkening, the resistance is re-established. If the bar of selenium be passed, while connected with the galvanometer, through the solar spectrum, its resistance is found to be most diminished at and beyond the red end of the spectrum, and the resistance is diminished most in those parts of the spectrum where the heat is greatest. The selenium, however, does not become sensibly warmer; and the slight increase of temperature it suffers, if supplied from a source of invisible heat, is not sufficient to produce the whole effect. It must be remembered, however, that the resistance of selenium diminishes with heat to 217° C., when the selenium melts, and the resistance suddenly and greatly increases.

314. Light caused by Resistance—Electric Light.—The heat being proportional to the resistance of a conductor, it follows that, when a metallic conductor is made very thin, and at the same time the electro-motive force is so increased that the current strength remains unchanged, the heat is accompanied by light, and the wire becomes incandescent. This intense heat, under these circumstances, may result in the fusion of the wire and rupture of the circuit. On bringing the metallic terminals near to one another, it is found that they may be brought to within $\frac{1}{1000}$ of an inch of one another, when the battery consists of 50 or 60 Grove's, without the slightest spark passing, or any indication of the passage of a current. On bringing the poles together, and again separating them by a very small interval, the act of separation is accompanied by a spark, due in the first place to the extra current, which partakes of the nature of frictional electricity. This spark, by vapourising a portion of the metallic poles, furnishes a vapour bridge with which the current passes. The + pole especially becomes heated; it melts and volatilises, and is carried with the current across between the poles, forming a bridge of incandescent metallic vapour, called an electric arch or arc. It seems, on the whole, that light cannot exist without matter. What we see is not electricity, but electrically incandescent matter. Further, the term incandescent must not be understood to be restricted to the exaltation of heat, but we must suppose that the molecular excitement called light may be produced by the direct action of electricity, without the intervention of heat. In the electric arc, however, heat precedes and accompanies light, for the origin is resistance. That matter is essential to the passage of the current appears from the fact that no current and no spark will pass through the most perfect vacuum.

315. The luminosity of the electric arc, when it takes place in air, is often increased by the combustion of the poles. Iron, lead, copper, etc., burn at the high temperature. Platinum, silver, etc., merely glow. The easy volatility of mercury permits that body to be used as the + pole as an abundant source of light. The most convenient substance is the dense form of carbon offered by coke. Thin pencils of this are fastened to the poles of a battery of about 40 Grove's cells. On being brought together and separated, a light of intolerable brightness results. Particles of carbon are torn off the + or platinum pole, and carried across the space in a state of intense incandescence. Some of them reach the − pole unburnt, but most burn, and so augment the heat and light. The + pole intumesces and softens; at its end a cup-like cavity is formed owing to the loss of carbon. The − pole becomes pointed, owing partly to the deposition on it of unburnt carbon, partly to its burning away. Beads of fused silicates and carbonates appear on the hot poles, and the coke itself is found to have been converted at the ends into graphite.

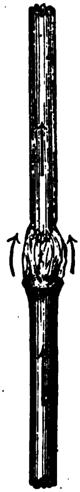


Fig. 269.

Analysed by the prism of the spectroscope, the spectrum is found to be continuous, showing that the light is mainly derived from solid matter; or, at least, that there is not sufficient gaseous matter to effect absorption of any of the rays. Metals placed in the cup of the + pole melt and volatilise, and give rise to characteristically banded spectra overlying the continuous spectrum of the carbon. The metallic arc acts towards a magnet as a current-bearing wire or spark discharge. It is pushed on one side by a magnetic pole, and may by such means be pushed out.

316. In *vacuo* the carbon points do not wear away by oxidation, and the gain of the − being about equal to the loss of the +, the poles remain for a long time at the same distance apart. Brought together under water, and again separated a short distance, the light is accompanied by the decomposition of the water, carbonic acid and carbonic oxide being formed. Brought together under bisulphide of carbon, a permanent gas is evolved, which can scarcely be anything but CS. The production of this gas does not depend upon the chemical nature of the pole, for it is also evolved when they are of platinum. Carbon poles brought together in an atmosphere of hydrogen, and separated so as to allow the arc to be formed, cause the hydrogen to unite with the carbon and form acetylene.

To ensure constancy of light when the carbon points are in air, and also constancy of position of the light, the points are moved towards one another by clockwork, in such a manner that the + moves faster than the –, to such an amount as to compensate for their unequal wearing away. The description of the very ingenious but rather complicated mechanical contrivances for effecting this purpose belongs rather to the science of mechanism.

317. Connection of Heat with Current Direction.—In Art. 90, *et seq.*, we considered the relation of heat to electrical discharge. It appeared, briefly, that a body rising in temperature lost its power of receiving or retaining + electricity before losing the power of receiving or retaining – electricity. Accordingly, we may roundly say that heat moves with + electricity. Further, when matter moves, heat moves, and therefore there is a tendency for matter and + electricity to move together. A few considerations in this direction may close this chapter. If a part of a platinum wire be heated red hot, and then connected with a battery, the hot part is seen to travel with the current. The motion of the + thermo-current, from the straight to the tangled part of a platinum wire, is probably due to the more rapid travelling of heat in the direction of the tangle, in consequence of the more rapid cooling there. The assertion must not be neglected, however, that when heat is carried along by a current, in copper the + current bears along the heat; in iron the heat travels against the current. In most cases, when two unequally heated pieces of the same metal are pressed together, the current travels with the heat from the hotter to the cooler metal. This is also the case when heat travels from a hot metal to a cold liquid. Inversely, if a *wire* between mercury cups becomes incandescent by reason of a current through it, the mercury nearest the zinc-battery poles becomes the hottest, showing that the heat has been carried with the current. When electrolysis takes place (Art. 189, *et seq.*) through a porous diaphragm, or through a siphon, there is an accumulation of the undecomposed electrolyte as well as of the electro-positive constituent around the – pole. Even when mixture or diffusion takes place, there is a current passing in the direction in which the matter mainly moves. When zinc dissolves in an acid, the balance of motion of heat is certainly away from the metal, that is, in the direction of the + current. It is not easy to reconcile the direction of heat motion with the direction of the current in the case of thermo-currents, in accordance with the known thermo-conductivity and specific heats of the metals. We cannot, at present, say that the direction of the current is determined by the direction of the maximum flow of heat.

CHAPTER XI.

OTHER SOURCES OF ELECTRICITY—RELATION OF ELECTRICITY TO LIFE.

318. Gas Battery.—In Art. 157, it was shown how the oxygen and hydrogen evolved during electrolysis strove to reverse the current by reason of their polarity. It is indeed possible to construct a battery whose action depends upon the polarity of electrolytically evolved gases. Further, if metals are used in contact with the gases which, like platinum, have the power of condensing the gases, it is not necessary for the latter to have been evolved electrolytically. A single cell of this description is shown in fig. 270. Two tubes, H and O, containing respectively hydrogen and oxygen, are inserted into a vessel V containing sulphuric acid. Through the tubes are fused platinum wires, terminating above in mercury cups, below in plates of platinised platinum reaching nearly to the bottom of the tubes. On joining the cups by means of a wire connected with a galvanometer, a current is found to pass round the circuit from O to H, through the galvanometer, or from H to O through the liquid. Both gases gradually disappear *forming* ultimately water. The platinum surface covered

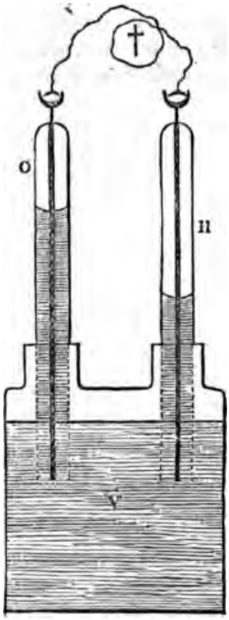


Fig. 270.

with hydrogen, acts as a zinc plate to the platinum plate covered with oxygen, which takes the part of the carbon, copper, or platinum of a single liquid cell. The effect is greater if, instead of chemically prepared gases, we make the tubes themselves the seat of electrolysis, and fill them with their respective gases by that means. We have then the gases in their most active condition (comp. Art. 157).

319. Electricity Affects the Senses.—The passage through the body of a discharge from a Leyden jar, is accompanied by muscular contraction and a nervous excitement or shock, which, however violent and unpleasant, can scarcely be called pain, but which more resembles a nervous start. Since we know that there must be continuity of motor nerve fibre from the seat of the will to the muscle for voluntary motion to be possible, it is plausible to suppose that the electricity acts upon the muscle by means of the nerves, and even that both the will force in motion and the sense force in motion are not other than electrical currents or signals sent to and from the head office. Many as have been the attempts to establish this theory, it must be at present admitted that there is absolutely no evidence to show that that which the nerves convey is electricity; and this although electricity can be detected both in the nerves and muscles, and although, indeed, it must be generated by the chemical changes at work throughout the body.

On moistening the hands, and laying hold of the terminals of a zinc-platinum battery of twenty cells, a slight shock is felt. If such an arrangement is made that the moisture of the hands is not electrolysed—and this may be done by plunging the electrodes into two cups of acidulated water into which the hands are then dipped—no sensation is felt during the continuation of the current; but a rather more powerful shock is felt when one of the hands is withdrawn. It is supposed from this that what is felt is the momentary induced current in the body, or what has been described in Art. 280 as the extra current. It will be remembered that the extra current, like all currents induced by make or break, is only of momentary duration; and since a large quantity has to pass in a small time, it acquires, as in the medical and Ruhmkorff's coil, a high tension, and is converted into frictional electricity. The physiological effect of muscular contraction, and the accompanying nervous commotion, depend for their amount not upon the quantity of electricity which passes through the muscle in a given time, but upon the amount of variation in current quantity in a given time. And this amount of variation depends both upon the rate of variation and the degree of each variation. Accordingly (Art. 297), the effect of a medical coil is increased by increasing the rate of make and break of the primary, and also, this being constant, by pushing the secondary further over the primary and magnet. It appears, then, that a galvanic current of uniform strength is almost without muscular effect; and that it is only when started, strengthened, weakened, or stopped that such effect follows; in other words, that galvanic electricity only has this effect as it gives rise to electricity of higher tension. Hence the incomparably stronger effects of the discharge from a jar.

320. Effect on Taste, Sight, and Hearing.—When two dissimilar metals, such as zinc and silver, are placed on opposite sides of the tongue, and then brought into contact, a flash of light is seen and a strong metallic taste is experienced. One naturally would attribute the metallic taste to the inevitable solution of the more electro-positive of the metals, under these circumstances, were it not that the metals are only in contact with the tip of the tongue, which is insensible to metallic tastes. Further, Dr. Stone has pointed out that, if wet sponges attached to the poles of a thirty cell platino-zinc battery be placed, one at the nape of the neck, and the other on the forehead, a metallic taste is instantly recognised. Some describe this taste as resembling soda water. We must admit, then, that the agitation of the nerves of the tongue or palate, by the establishment of a current through the head, gives rise to this sensation. But why it should be this particular taste, rather than sweet or bitter, is quite obscure. The application of the terminals as above, is also accompanied by a momentary but intolerable blaze of light. Placed in the ears, the terminals of the battery of thirty cells give rise to a continuous sound. As there is no excessive sound either on closing or opening the circuit, it is not impossible that this sound is connected with a process of electrolysis, which indeed it suggests. The sense of smell seems never to be awakened.

321. Although, as above stated, there is no proof that nerve-force is electricity, and although nerve fibre conducts neither sensibly better or worse than muscular fibre or other tissues, and although there is no provision for the electric isolation of the nerves, yet the nerves receive and distribute electric excitement to the muscles; or, to speak more cautiously, they receive electric excitement, and transmit their own force to the muscles. Further, there appears to be a greater potential in the muscles than in the nerves, or, what comes practically to the same, in the extremities than in the brain. Thus, if the nerve of a frog's leg be laid bare from the knee to the thigh socket, we find that it is at once an electrogen and an electroscope. If the toes are wrapped round with a platinum wire connected with one terminal of a delicate galvanometer, and the nerve is fastened to another wire connected with the other terminal, the needle is strongly deflected, and shows a current passing from the muscle to the nerve (from the toes towards the head). This current is permanent for many hours after death. The same direction of current, with greater energy, is observed if the same connection is made with the toes and nerves of the living animal, which is then induced to contract its muscles. Inversely, platinum wires being fastened to the toes and nerve, the slightest electrical current sent through causes muscular spasmodic contraction of the muscles. The exhibition of the prevailing electric tension does not require the isolation of the nerves. It is found that if a skinned frog have its legs placed in one cup and its head in another, a current passes from the former to the latter when they are connected. Further, if the nerves of a frog's leg be removed as completely as possible, and the leg be bent at the knee so that the toes are in one cup and the thigh in another, a current will pass from the first to the last when they are connected.

Experiments in this direction are attended by very many sources of error. To get rid of one of them, namely, that arising from the possible generation of a current through the contact of metals with dissimilar organic liquids, the parts of the animal under experiment are sometimes laid upon many folds of bibulous paper, soaked in acid or brine; and, to avoid chemical reaction between the liquid in the animal and that of the paper, moist membranes are interposed. Very many of the results obtained are delusive, on account of the inevitable osmose and consequent current.

322. The only conclusive instances of electricity entering as an essential into the animal economy appear to be those offered by certain species of ray and eel. The torpedo or electric ray is furnished with many hundred polygonal columns of cartilaginous walls; these are placed side by side like basaltic columns. Each column consists of parallel plates of cartilage, whose planes are perpendicular to the axis of the column. The plates are separated from one another by mucilage. This columnar mass reaches from the back to the front of the fish around the edge, and is singularly suggestive of a collection of Voltaic piles. If the belly of the fish be placed on a sheet of metal which is touched by one hand, while the back of the fish is touched by the other, a shock is felt, due to an electric discharge from the back, through the experimenter, to the belly. Owing to the conductivity of salt water the ray can, by its electric discharge, benumb fishes at its side. Possibly, the chief use of the electric organ may be as a means of defence from predatory fish. It is quite unknown how the electricity is accumulated, and how discharged. In the electric eel or gymnotus the columns are in the unusually long tail; they run parallel with the vertebral column; their plates are accordingly transverse to this column, and the polarity is from head to tail, the head being positive.

323. The evidence to show that electricity plays an essential part in vegetable life is very insufficient. Currents will indeed pass from one part of a fruit to another when it is pierced by the terminals of a galvanometer. Germination is also said to give rise to a current. But when we remember that capillary motion, osmose, and difference of composition of the vegetable juices in contact with the electrodes, are all competent to start currents, we must interpret such experiments with great caution. Certain plants have the power of closing their leaves when mechanically irritated, especially by nitrogenous bodies. Furnished with bristles, and capable of excreting a clammy and acrid juice, the plant is enabled to entrap and digest insects. If two points of the back of the midriff of such a leaf are connected with a galvanometer, and the leaf is then irritated, a current is established through the galvanometer. This would seem to indicate that the motion of the leaf, like that of a muscle, is accompanied by electric discharge. It is possible, however, that the excretion which occurs when the leaf closes may act as a liquid element in a couple, and start the current.

324. Although there is this somewhat intimate connection between nervous and electric excitement, it is noteworthy that the strongest current in a coil does not affect the thought when the coil is placed as a cap on the head. Nor does thought determine a current in a coil around the head. Some recent experiments are said to show that an electric current is determined between two points of the retina when one is illuminated and the other not.

CHAPTER XII.

ELECTRIC TELEGRAPH AND CHRONOSCOPE.

325. General.—Not long after the exceptional conductivities of the metals were established, attempts were made to convey signals by charging one end of an isolated wire with frictional electricity, and diverging the gold leaves of an electroscope at the other. Under favourable atmospheric conditions it was found possible to convey a signal by this means through several miles. Such electricity requires, on account of its high tension, more perfect isolation than can be easily insured; and the action of the machines were too uncertain to allow the practical use of such a device. The second great step was the employment of Voltaic electricity. A magnetometer (see Art. 352), having a long enveloping wire, was set up at the receiving station. At the signalling station a current in a primary was made and broken. The insulated wires connected with the magnetometer, and leading thence to the signalling station, were arranged there so as to form a secondary. The magnetometer needle, carrying a reflector, was accordingly turned one way or the other at will, either by making, breaking, or reversing, the primary current. Next, though not in historical order, may be mentioned the observation that, for a current to pass, it is not necessary for the circuit to be metallic throughout. The earth itself may be utilised in place of the return wire, provided the wire-ends, where the return wire may be supposed to be cut off, are in good and ample connection with the earth. Next, the direct current was made to pass round one of a pair of vertically supported astatic needles at the receiving station; the direction of the current at the signalling station being reversible, the needle could be turned to the *right or left* at will, and the number and sequence of right and left movements furnished a signalling code. Next may be mentioned the development of considerable mechanical force at the receiving station by sending the current through a coil of wire there surrounding a bar of soft iron. The so-formed electro-magnet can, by its attraction, so move a style as to make a permanent mark on a uniformly-moving strip of paper. And this mark may be a dot or a line, according to the duration of the electro-magnetism, that is, at the will of the sender. By the combinations of these a code may be formed. The style may be replaced by a pencil, between which and the paper there is a chemical action. Again, instead of a battery, the current may be generated from a permanent magnet, as in a magneto-electric machine. If the wire be isolated thoroughly it may pass for thousands of miles beneath the sea; and the same wire may be transmitting two signals at the same time. A current which, on arriving at a station, may reach it in such a state of exhaustion owing to the great resistance, as to be unable to do much work, may still be sufficiently strong to connect a battery at that station with the wire beyond, or with a printing machine. Such an auxiliary current is called a relay.

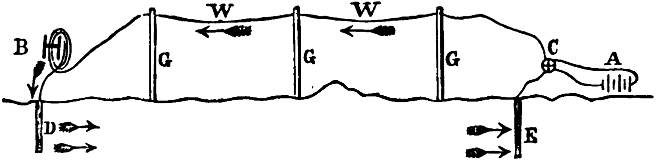


Fig. 271.

326. The Needle Telegraph may be understood in principle from fig. 271. Let A be the battery in the signalling station; its terminals are in connection with the rheotrope C (Art. 268). The other connections of the rheotrope are one of them fastened to a large cast-iron plate E, sunk in the earth; the other is connected with the air-wire W, which is hung from the telegraph poles G, G, by means of porcelain eyes, or hooks fastened in inverted earthenware cups. The wire reaches the receiving station B, and there passes round the hindermost needle of an astatic pair, after which it reaches the earth through a plate D, similar to E. C may be so turned as to shut off all current, or the + pole, or the – pole may be connected with W. The needle at B turns accordingly. It is prevented from turning too far by a stop. It is sometimes stated that the current actually returns from D to E. No doubt, for the + current to pass, say from A to B, + electricity must leave D, and + must reach the zinc through E. But it is both unnecessary and unreasonable to suppose that it is the same which enters E as left D. Compare the circulation of the electricity with that of water in a pipe connecting two parts of a marsh, and forced to move by a pump at one end. It remains full by the indrought at one end, and the escape at the other. Work, say of a water-wheel, can be done at the end B, as effectively as though the water passed through a return-pipe from D to E, provided there is a free escape at D, and a free ingress at E.

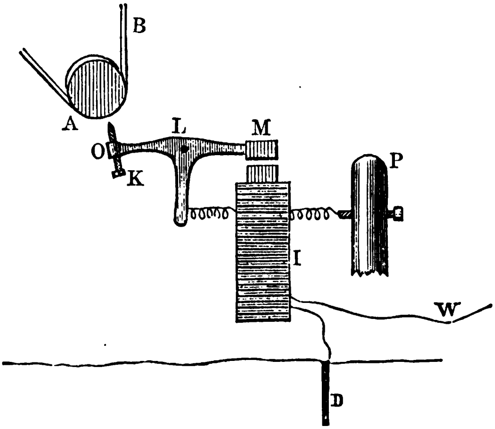


Fig. 272.

327. The Printing Telegraph is shown in the sketch, fig. 272, which represents the arrangement at the receiving station. W is the isolated air-wire. This passes round the soft iron core I, and thence to earth at D. Immediately *above I is a* bent lever, O, L, N, M, C, of which the fulcrum is at L. At N is a spring, the other end of which is fastened to a screw through the pillar P. At M is a mass of soft iron. Through O passes the adjustable pencil K. Above its point is a little drum or reel A, which revolves by clock-work not shown, and which carries with it a paper tape B, which receives the message. Connection being made at the signalling station, I becomes an electro-magnet, M is pulled down, the spring, S, being stretched. The lever turning around L raises the pencil K, which marks the moving paper, if the current be continued, in a line; if it be momentary, in a dot. For, on breaking the current, the spring S pulls N towards P, and so pulls the pencil away from the paper. To prevent the pencil pressing too hard upon the paper, the end C is so adjusted that it touches P before M touches I, and before the pencil or style can get too close to the reel. The style, instead of marking the paper, is sometimes made to press the paper upon a little drum, the surface of which is covered with printer's ink. The sending and receiving arrangements are shown in fig. 273 (Müller Pouillet).

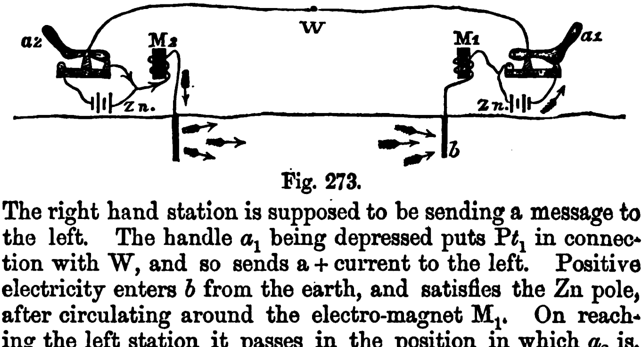


Fig. 273.

The right hand station is supposed to be sending a message to the left. The handle a_1 being depressed puts Pt_1 in connection with W, and so sends a + current to the left. Positive electricity enters b from the earth, and satisfies the Zn pole, after circulating around the electro-magnet M_1. On reaching the left station it passes in the position in which a_2 is, through M_2 to the earth. None of it goes to Zn_2, for that circuit is not closed. M_1 and M_2 are made simultaneously into electro-magnets. If a_1 be raised and a_2 depressed, a + current is sent in the opposite direction. It is usual for a_1 and a_2 to be kept raised by springs when they are not depressed by the hand in signalling. Instead of marking or punching holes in the paper a bell may be rung; and, indeed, this is generally the first signal sent to arrest the attention of the recipient. Only the electro-magnets of the printing appliances are shown in fig. 273.

328 Relays.—The action of these may be understood from fig. 274. Suppose the + current reaches the station through the wire W. Instead of employing it to work the printing apparatus directly, it passes round the electro-magnet, which pulls down the mass M, turning the lever N, O, M, about O, and thrusting B forward till it touches C. The wire C is wrapped round the electro-magnet E, after which it passes to the + pole of the local battery L, whose zinc pole is connected with earth. When C touches B the whole strength of the local battery is added to the residue of the distant one, and E is strong enough for printing.

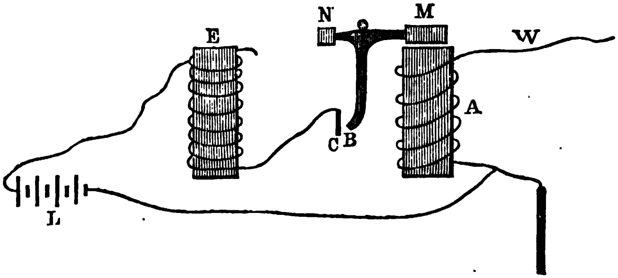


Fig. 274.

329. Submarine Telegraphs.—For telegraph wires which have only to pass for short distances under the earth, as in towns, the copper wires are usually covered with a sheathing of india-rubber or gutta-percha, or some mixture of these with resin, marine glue, or silica, supported by a web of calico. When more perfect isolation, great strength, and density approaching to that of water are required, as in long submarine cables, the bundle of copper wires, which act as one wire to convey the current, are seven in number. They are embedded in purified gutta-percha. This is again covered with jute, and finally it is protected by stout hemp, covered iron, or steel wires being wound upon it. Scarcely any two cables are alike, and it remains to be seen which has the most perfect form. The great resistance offered by the enormous length of most submarine cables renders it impossible to employ the current for printing. A reflecting galvanometer is employed, such as was described in Art. 276, and this may be astatic. The motion of the spot of light is read off, and the same code is adopted as in the needle telegraph. The resistance of the core of the cable can be measured before it is immersed. The total want of insulation, leakage, or the conduction of the insulator, can be measured when the cable is in a tank of sea-water, by finding what proportion of the current is lost.

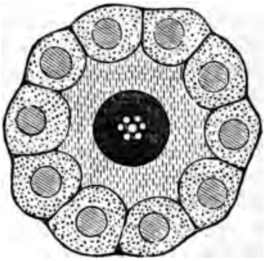


Fig. 275.

Supposing the insulation to be perfect, a long cable gives the means of showing certain electrical laws, such as—

330. Inductive Capacity.—The conditions of conversion of Voltaic into frictional electricity are partly fulfilled in a long, well insulated cable. If the wire of such a cable be united to one pole of a battery, and the tank containing the cable be connected with the other pole or with the earth, a current of electricity enters the copper of the cable, although it has no outlet. It comes to rest; it spreads itself on the surface of the copper, and fixes itself there. It summons electricity of the opposite kind from the earth and water; and this induced electricity gets as near to that of the wire as possible, the one on the inside, the other on the outside, of the dielectric tube of gutta-percha. The current is converted into frictional (the dynamic into static) electricity. This pouring in is shown by the deflexion of a galvanometer interposed between the battery-pole and the wire. If the battery be disconnected, and earth connection made, the electricity pours out again, and the galvanometer needle turns in the opposite direction. It enters as current electricity, exists as condensed or static electricity, and again leaves the wire as current electricity. The cable is, in short, a condenser or Leyden jar. The quantity of electricity which can thus be made to enter a cable varies directly with the electro-motive force of the battery; two tandem cells throwing in, under like conditions, twice as much as one, if the potential of the water is constant (say zero). This condensation only taking place by the condensation of the electricity of the opposite kind, it follows that, when the dielectric is very thick, but little such condensation is possible through it. If it is very thin, and yet a perfect insulator, the condensation is at its greatest. In an air-line the thickness of the dielectric air is enormous, and condensation is insignificant. It is sensible in earth wires (inclosed in tubes) and in tunnels. For a given thickness of dielectric it varies with the surface of the wire, that is, with the length of the wire and with the square of its diameter. The relation between the effect of increased thickness of dielectric and increased surface is such that the quantity which enters a wire from a given battery would remain the same if the wire, with its covering, were simply magnified or proportionally increased in sectional dimensions. The quantity of electricity which can be thus thrown into a cable is called the inductive capacity or electro-static capacity.

331. This accumulation of electricity in a wire, or what we may almost call absorption of electricity, gives rise to a drag upon the current which passes through a cable thus saturated. When the current enters, its first act is to lay down condensed electricity on the inside of the dielectric. The head of the advancing column of electricity reaches the end much weakened by this diminution. Only the later parts find this duty performed for them, and pass on undiminished. The first part may never reach the end at all. Accordingly, the effect at the distant end resembles that of a wave of sensible length. The maximum effect is not brought about immediately. Hence some time must elapse before a second signal is sent. This difficulty is overcome by the device of sending a negative into the wire immediately after the positive. The one wave does not overtake and destroy the other, but it sweeps the wire clean of residual positive.

332. Velocity of Voltaic Electricity.—The velocity of a spark discharge, travelling through a copper wire 1·7 in. *in thickness,* was found to be (Art. 110) between one and two hundred thousand miles in a second. The velocity of Voltaic electricity is much less. The mean of a number of experiments, in which thick iron wire was used, showed a velocity of only seventeen thousand miles per second in an air line. In submarine cables, where inductive capacity is great, the rate is much slower. In the Atlantic cable two-tenths of a second elapse before any effect is produced (ten thousand miles a second). In one second about half the maximum is reached. Three seconds are required for the maximum effect to be produced.

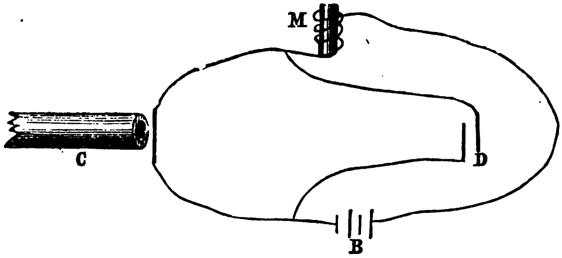


Fig. 276.

333. The Electric Chronoscope.—Very short intervals of time can be measured by the establishment and cessation of the electric current. Thus, the time required for a cannon-ball to pass through a hundred yards, can be measured in a manner shown in fig. 276. It is at once seen that the current is broken during the flight of the ball from C (when it breaks the wire at the mouth of the cannon) to D, when it momentarily completes the circuit. M becomes an electro-magnet during that interval. It is easy, by means of a spring acting against the electro-magnet, to pull a keeper from it and to let a clock be in action as long as no current passes.

BOOK III.

MAGNETISM.

CHAPTER I.

LODESTONE—THEORIES—POLARITY—INDUCTION.

334. We have had to examine many of the properties of magnets in considering electro-magnetism; for the study of the relation of a magnet to a current was necessary for the proper examination of the current. We have now to consider the properties of magnets apart from the origin of their magnetism.

Lodestone.—The oxide of iron whose composition is $Fe_3 O_4$, and which may be regarded as a mixture of FeO with Fe_2O_3, is sometimes found in laminar masses which attract iron filings and cause them to adhere in tufts about the mineral, which attract and repel different parts of other masses of the same mineral, and which, when hung in flakes from slender threads in vertical planes, often adjust themselves nearly north and south. Some specimens of the sulphides of iron have been found to have the same properties in a lesser degree. If two such flakes, which point north and south, are so brought near to one another that the two ends which pointed to the north are near to one another, they are found to repel; so are the two poles which point to the south; while the north-pointing pole of the one attracts and is attracted by the south-pointing pole of the other, and *vice versâ*. We shall call the end or part of the lodestone which points to the N. the N.-seeking end, and suppose that it is endued with N.-seeking magnetism. The other is the

S.-seeking end, and is endued with S.-seeking magnetism. The like named magnetisms, or ends endowed with such, repel one another; the unlike named attract.

If one-half of a small steel needle or other rod be rubbed with a N.-seeking part of a lodestone, and the needle be then hung about its centre of gravity, the rubbed end will point to the S., and this adjustment will be more forcible if the other end be rubbed with a S.-seeking part of the lodestone. Each half of the needle acquires the opposite kind of magnetism to that with which it is rubbed. If one-half of a second needle be rubbed with the N.-seeking end of the first, and the other half with the S.-seeking end, the second needle will also point N. and S., and its N.-seeking end will be that which was rubbed with the S.-seeking end of the first needle. It follows that the two parts of two needles which have been rubbed together attract one another. The needles are said to have acquired magnetic polarity. If such magnetised needles or similarly magnetised bars of steel are sprinkled with iron filings, the latter collect in greatest abundance very near the ends. The regions where such attraction is the greatest, are called the poles of the magnet.

335. Names of Magnetic Poles and Polarity.—If a strong bar magnet be laid on the table with its N.-seeking end to the right, fig. 277, a magnetic needle supported above this will place its own S.-seeking end above the N.-seeking end of the latter. If now the fixed magnet is removed, the little magnet will set itself N. and S. If this be due, as it unquestionably is, to the fact that the earth itself is a magnet, the end of the little magnet which points N. must do so because its magnetism is of the opposite kind to that about the geographical north pole. If we call the magnetism N. magnetism which resides in the N.-seeking end of the needle; then there must be S. magnetism at the N. pole. Or, if we choose to define the magnetism at the N. pole as N. magnetism, we must look upon the north pointing pole of a magnet as possessing S. magnetism. In the present treatise I have already adopted,

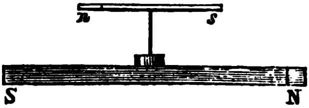


Fig. 277.

and shall use the term N.-seeking to denote the kind of magnetism in the end of the needle which points to the north, to distinguish it from the magnetism which resides at the N. pole, and which on that account it is difficult to get generally called S. magnetism, and I shall denote by N., as I have already done, that end of a magnet which points to the geographical north.

336. Theories of Magnetism.—Before the near relationship between current electricity and magnetism was established, and Ampère's hypothesis entertained, two theories were much in vogue to explain magnetic polarity; and it is for many reasons as well that they should be remembered. The one may be called the two-fluid theory, the other the molecular polar theory. In the first, a mass of iron or steel is supposed to have a certain amount of two magnetic fluids of unlike kinds, and always equal in quantity one to the other. In a magnetised lodestone or bar of steel these fluids are separated, but endeavouring to unite to form a neutral fluid. On magnetising a bar of steel by rubbing its two halves with the opposite poles of a magnet, the neutral fluid is decomposed, and its constituent fluids are accumulated in the halves which have been in contact with the unlike poles of the exciting magnet. In the case of soft iron the two fluids unite immediately after the exciting magnet is withdrawn; in the case of steel there is a resistance to the separation of the fluids, and also a resistance to their reunion. This resistance is called the coercive force; and the name is used whatever theory of magnetism is adopted. In the molecular polarity theory each particle of the iron or steel is supposed to have a N. and a S.-seeking pole. In the ordinary state these particles are so arranged that there is a uniform distribution of molecular polarity throughout the mass. Or, what comes to the same thing, the particles are arranged in perfect confusion. The resulting polarity of the mass is then nothing. If, however, the particles, or some of them, can so turn round that the poles of like name are all in one direction, the whole mass will then have polarity. An illustration of this motion may be made by filling a narrow tube with steel filings and magnetising it as one would a bar of steel. It becomes, as long as it is undisturbed, a permanent magnet. On shaking it up the polarity of the particles is mixed and the whole mass losses distinctive polarity.

Against this fluid theory the following experiment argues rather forcibly:—If a ribbon of hardened steel be magnetised so as to become a permanent magnet, and then broken in the middle, each half is found to be a perfect permanent magnet not less strong than the original. Each half may again be broken in half, and so on, till the fragments are broader than they are long. All the fragments have their like poles in the same direction, fig. 278. It is difficult to conceive two fluids so nimble in their motion, as to rush in both directions across the line of fracture, and establish themselves on the opposite side of the crack. The theory of molecular polarity satisfies the experiment more satisfactorily; for, from fig. 279, it is seen that wherever the rupture between contiguous particles takes place, the exposed ends have always their proper polarity. Of course the same preservation of polarity holds good on the current theory of Ampère.

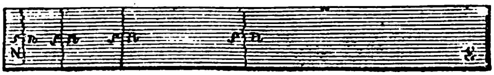


Fig. 278.

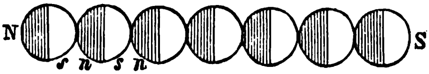


Fig. 279.

337. Polarity Essential.—Whatever theory is most acceptable, the fact remains that while with frictional electricity we can charge a whole body with say + electricity, or raise its potential above that of the earth, we can, under no circumstances, give to a piece of steel or iron magnetism of exclusively one kind. If we rub a thin piece of steel from end to end with one pole, say the N.-seeking, of a magnet, whatever little magnetism it acquires will still be polar, that is, the end last touched will be left S.-seeking. If the two ends be rubbed simultaneously with (say) the S.-seeking poles of two equally strong magnets, we shall find that one S.-seeking pole is in the middle. And on breaking the magnet there, we find we get two perfect magnets with polarity equal at the two ends, and the one equal to the other. In the same mass of steel there is always as much, and no more, N.-seeking polarity as of S.-seeking. This even extends to the magnetic shells, which will be considered in Art. 340.

338. Induction.—Though there is this great distinction between high tension electricity and magnetism, there is a very perfect analogy as far as induction is concerned, especially when, as is the case with soft iron, no permanent magnetization ensues. If, fig. 280 (1), a piece of soft iron, F*e*, is placed in the neighbourhood of the N.-seeking end, N, of a permanent magnet, the S.-seeking end of a needle, *n s*, will be attracted to the end of F*e*, away from the magnet. This shows that the iron is temporarily polarised at a distance, in the same manner as the steel is permanently magnetised by contact. This action is closely parallel to that suffered by a conductor (2) isolated and exposed to the + conductor of a machine. That the attraction of the needle is not through the iron towards the N. of the permanent magnet can be shown by an arrangement like that of fig. 281. Here we have a flat bar of soft iron, F*e*, hung in a stirrup above a permanent magnet, N S. It places itself exactly parallel to that magnet. If, now, the S.-seeking pole of another permanent magnet be brought near that end of the soft iron which is above the N.-seeking pole of the permanent magnet, repulsion ensues, the slung bar swings away, the S″ pole is then

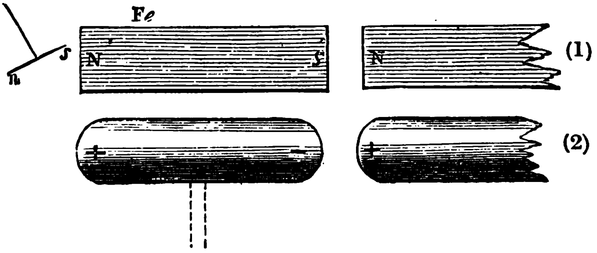


Fig. 280.

removed, and only brought back when the soft iron is just above the magnet, and moving away from the experimenter. By repeating this a few times the bar, Fe, can be turned so as to swing through 45°. The experiment, of course, shows that the magnetism induced in that end of Fe, which is above the N.-seeking, is itself S.-seeking. A piece of soft iron, laid with one end on the end of a magnet, simply prolongs that end; and the same effect follows by induction when the two are only near to one another. The induced soft iron magnet can itself exert an inductive effect on a second piece of soft iron, so that, from a powerful magnet, a number of soft iron nails may be hung one from the other. The induction from a distance sometimes produces effects apparently anomalous. Thus, if a soft iron bullet be put in a cardboard tray, and

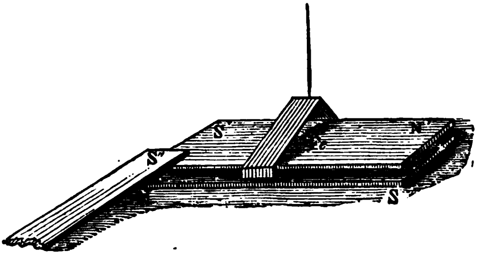


Fig. 281.

Fig. 282.

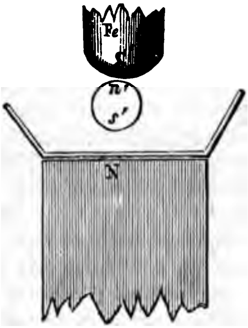


Fig. 283.

placed over the end of a magnet, a mass of soft iron brought to touch the top of the bullet may be able to lift it. It seems as though the magnetism of the magnet had called into being a force greater than itself. This is not so; but the force which is developed, though less than the developing force, acts at a lesser distance, and, therefore, at a greater advantage. If the N.-seeking end of the magnet is used, the bullet B undergoes magnetic inductive analysis, as is shown in the figure. The soft iron, F*e*, is also inductively magnetised, its S.-seeking magnetism descending. This is assisted by the action of the *n* of the bullet upon F*e*. The induced magnetism of B and F*e* attract one another with, it is true, less force than N would attract *s* if they were in contact, but with more force than is exerted between them when separated by the cardboard. For a similar reason, by placing the one pole of one magnet beneath the opposite pole of another, more iron bullets can be attached to the latter than when this is not the case. It appears at once from the figure, 284, that, by placing the S.-seeking pole of a magnet beneath the lowest of the bullets hung from N (1), the analysis of their magnetism is confirmed and assisted. And although S tries to assist gravity and drag the lower bullets away, it acts more effectively in binding them together, because the increased polarity it induces acts between the bullets at a very much less distance than that at which it itself acts directly. If the N.-seeking, instead of the S.-seeking pole of

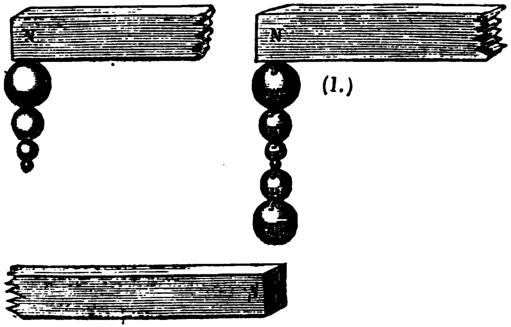


Fig. 284.

the second magnet is brought beneath the lowest bullet, they all drop off. Or, if the S.-seeking equally strong pole of the second magnet be placed upon the N.-seeking of the first as it is supporting its greatest number of bullets, many of them fall off; for the analysis of their magnetism is partly reversed. This may be well shown in fig. 285, where a suspended iron bullet, *b*, is attracted by a magnet, N S, from which it is separated by a glass sheet, G. It is pulled out of the plumb, and rests against the glass. Another magnet, S′ N′, brought along the first will release the ball *b*, by endeavouring to analyse its magnetism in an opposite sense. It comes to the same thing if we suppose the two equally strong magnets to neutralise one another, so that no force is left for the bullet. In fact, if any number of equally strong steel magnets, all having their N.-seeking poles in one direction, be mixed with an equal number of equally strong magnets, having all their N.-seeking poles in the opposite direction, we get a bundle in no way to be distinguished from a bundle of unmagnetised rods.

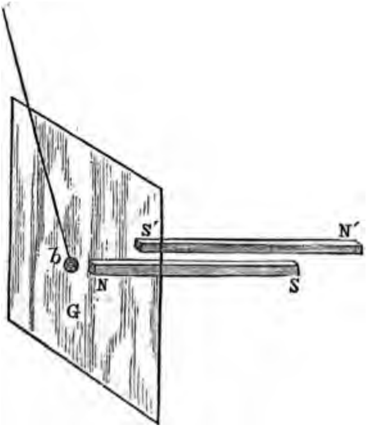


Fig. 285.

339. Magnetization.—With thin strips of steel which require magnetization, it usually suffices to rub both sides of each half in succession upon the opposite poles of a permanent magnet. But for magnets of considerable thickness, a more systematic method is preferable. The piece of steel to be magnetised is placed, fig. 286, between the opposite poles, N and S, of the permanent magnets, E and F. The permanent magnets, A and B, are then applied, as in the figure, and moved at the same rate, A towards C, and B towards D, A having its N.-seeking, and B its S.-seeking end in contact with C D. After ten or twelve such strokes, the bar C D is turned over about its long axis, and the same process is repeated on the other side. For thicker rods or strips it is said to be preferable to separate the lower ends of A and B by a piece of wood, and to move them together to and fro as far as the ends of the rod. This process is also to be repeated on the other side. For many purposes it is advantageous to have the opposite poles of a magnet close to one another. The magnet is then bent round so as to form a horse-shoe shape, which is the most usual shape of the toy magnets, and often also of the most powerful electro-magnets.

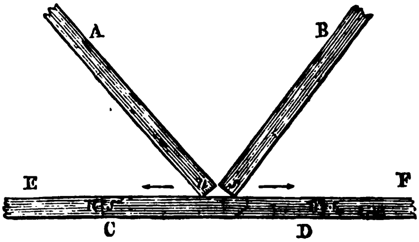


Fig. 286.

To magnetise these, their ends are connected with a soft iron plate; and the ends of a similar horse-shoe magnet are dragged along the receptive one from the bend to the ends. Or the single pole of a bar magnet is rubbed round and round the horse-shoe and soft iron always in one direction.

A piece of steel, which is allowed to cool from a red heat between magnetic poles, is found to be very uniformly magnetised. Also if, having a horse-shoe shape, its two ends are placed against the poles of an electro-magnet, and when in this position it is continually hammered, it soon acquires strong magnetism. It is noteworthy that, while iron is instantly magnetised by a current passing in a coil round it, a steel bar is but feebly magnetised under these conditions, although the current may pass for a long time. If a short coil, embracing only a small part of the steel bar, be moved from the centre to one end, the magnetization is much more complete.

340. Other Kinds of Polarity.—The foregoing plans are used when we wish to get the most complete dual distribution of the magnetism. The magnetism, may, however, be distributed in a great variety of other ways. If, for instance, a number of bar magnets, *a*, *b*, *c*, *d*, *e*, are arranged so that their *n* poles touch one another, and a steel ribbon, *f*, be rubbed upon them up and down, vertically, the ribbon becomes magnetised as marked, namely, in the example there are four intermediate poles formed. These are called consequent poles, and their occurrence has to be avoided when one wishes to magnetise to the uttermost. Further, it is not only possible to build up a magnet by fastening magnets side by side, but it is possible to magnetise a bar of some thickness so that its internal polarity is the reverse of its external—fig. 288. Such antagonistic polarity, however, is by no means permanent.

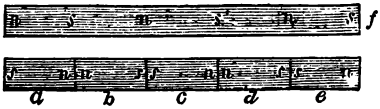


Fig. 287.

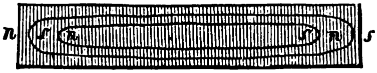


Fig. 288.

341. Keepers and Armatures.—An armature, properly so called, is a piece of soft iron laid along the similar poles of a mass of lodestone, which enables thereby the similar poles to reinforce one another, and to manifest their joint effect at the end of the soft iron mass. A keeper is a piece of soft iron connecting the dissimilar poles of a horse-shoe magnet, or a pair of straight ones. Each end of the keeper acquires temporarily the opposite kind of magnetism to the pole with which it is in contact. The induced polarity in the keeper K, fig. 289, caused by one pole, is confirmed by that of the other. We may look on a magnet so furnished with a keeper as a closed magnetic circuit. It is self-sufficient; and is not affected by its attitude towards the magnetic poles of the earth. Deprived of its keeper, a magnet gradually loses

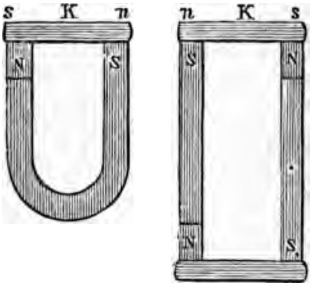


Fig. 289.

its magnetism, unless accidentally placed with its poles N and S, and, indeed, with its S.-seeking pole towards the S. And this loss depends upon the fact that a bar of steel is more easily demagnetised than magnetised. A steel horseshoe may be drawn twenty times upon a permanent horseshoe magnet, and acquire thereby almost its maximum polarity. But if its position be reversed, so that the end which comes into contact with the respective poles are reversed, one single stroke will completely deprive it of magnetism. A keeper need only touch the poles by an edge. And, indeed, judging of the effectiveness of a keeper by the force required to tear it away, a rounded keeper is more effective than a flat one, for the former requires a greater force for rupture.

342. Compound Magnets.—A magnet of great strength can be made by riveting together sheet magnets which have been magnetised as much as possible. Such magnets may be placed side by side, and only connected together by masses of soft iron at their ends; or they may be in actual contact. In the latter case there is almost a certainty that, in the course of time, the polarity of some of the elementary magnets will be found reversed, thereby, of course, diminishing the joint effect. The most powerful magnets are made by placing side by side a number of similarly magnetised steel wires.

343. Supporting Power.—If the keeper of a magnet be repeatedly and suddenly pulled off, the magnet diminishes in power. But if a weight be hung to the keeper of a magnet just insufficient to pull it off, it is found that the weight may be gradually increased far beyond that which the magnet was at first competent to carry. When rupture at last takes place the magnet is not, however, found to be permanently strengthened; it is found to have very nearly the same sustaining power that it had before the increase commenced. The maximum sustaining power of permanent magnets is at present by no means exactly ascertained. Small magnets may, however, be made to sustain, in comparison with their weight, more than large ones. To connect the weight of a magnet with its greatest sustaining power the formula

$$S = a\sqrt[3]{w^2}$$

has been experimentally deduced; but it requires confirmation.

CHAPTER II.

THE EARTH A MAGNET.

344. Before examining quantitatively the magnetism of artificial magnets, it is necessary to consider briefly the magnetism of the earth; because this is an inevitable factor in all magnetic measurements. If we conceive a huge magnet, thrust through the axis of rotation of the earth, having its N.-seeking pole at the S. geographical pole, and its S.-seeking pole at the N. geographical pole, we get the first crude notion of the earth's magnetism. By the action of such a magnet a magnetic needle at the equator would set itself horizontally, and would remain horizontal at all points of the equator. Advancing polewards along a meridian we should, in the northern hemisphere, find the needle lose its horizontality, and "dip" more and more, so that, if produced, it would cut the earth. At the north pole the needle would stand vertically, with its N.-seeking pole downwards. Subject to certain alterations this is what actually occurs when we travel with a needle about the earth; and, accordingly, the earth is to be regarded as a spherical magnet, having its N.-seeking magnetic pole at the crown of the S. hemisphere, and its S.-seeking magnetic pole at the crown of the N. hemisphere.

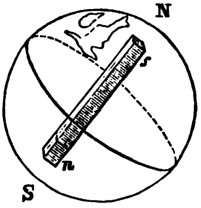


Fig. 290.

345. Cause of Earth's Magnetism.—The known earth's crust contains abundance of iron and other less strongly magnetizable metals, chiefly as oxide and compounds of the oxide. Iron pervades all "primary" and "secondary" rocks, and forms an essential part of innumerable minerals. Compounds of iron, as we have seen in the lodestone, are capable, as well as iron, of receiving and retaining magnetism; but the source of this magnetism is not at all clear. Perhaps the least unsatisfactory explanation is the following: the earth, turning towards the east, offers more and more westerly parts of its surface to the solar radiation. The thermal effect is the same as though a flood of heat travelled around the earth from east to west. We have seen many instances which show that heat and electricity travel together; that, in a closed circuit, if we can get heat to circulate, the + current travels with it. There may, therefore, be prevailing earth-currents moving "with the sun" from east to west around the earth. The earth being magnetizable, these currents would convert it into an electro-magnet, having its N.-seeking magnetism at the S. geographic pole, where it is actually found. The light of the aurora, which seems to have its greatest activity at the poles, is not unlike the light seen on making a strong electro-magnet in a dark room. Variations in the earth's magnetism may be supposed to be the cause of these lights, which are sometimes wrongly looked upon as the cause, instead of, as they possibly may be, the consequence of the magnetic disturbances or "storms" which so generally accompany, and, indeed, precede them; and which are not attended by any disturbance of the electrical condition of the air.

346. Compass and Distribution of Magnetism on the Earth.—A compass is a magnetic needle, so supported that it can only turn in a horizontal plane. This is effected by boring it through the middle, and cementing an agate cap to the upper side over the hole. A hard steel point serves as a pivot. The ends move over a circle, which in marine compasses is divided into 32 divisions by 32 "points." The marine compass and card are usually inclosed in a case which turns on gimbals, so that mere rolling does not disturb it. The compass needle is often fastened to the bottom of the card, which then turns with it. There is then a fixed vertical line marked on the cylinder in which the needle and card turn. Such line is, of course, in the vertical plane running fore and aft amidships. When the divided card is made movable, two or four parallel magnets may be attached to it.

The most exact observations are to be made with a single needle turning on a point. For a long series of observations at the same place, the position of the needle is sometimes *registered* by making its axis carry a mirror, the light reflected from which falls upon a roll of sensitive paper in uniform motion. In all cases the needle is found not to be quite true, that is, its magnetic axis is not identical with its geometric one. This defect is corrected by simply turning it over, when, if the two readings differ from one another, the true reading is half way between them.

A steel bar balanced on knife edges, the continuations of which are at right angles to it and pass through its centre of gravity, will be able to turn only in a vertical plane, and will remain at rest in any position. Let it now be magnetised and placed so that its plane of possible rotation is the vertical plane passing through the compass needle. The N.-seeking end will, in the N. hemisphere, dip downwards; the whole needle becomes inclined. Such a needle is called an inclination needle, or dipping needle. Its motion may be made self-registering as with the horizontal needle; and errors of construction are eliminated by turning it over sideways; it being movable on its axis. We may conveniently divide magnetic terrestrial observations into two classes—those variations which occur in the same place, which we may call variations in time; and those which are due to difference of locality, variations in place.

347. Declination in Time.—The most immediate result of examining the direction of a horizontal needle in (say) London is, that it does not point to the true north, but about 17° west of north. This angle, which is the angle made between two vertical planes, one passing through the earth's axis, and the other through the needle, is called the declination. Observations extending over nearly three hundred years, enable us to deduce the gradual change in the mean declination of the needle, or, as it is called, the secular change.

Year.	Declination.	Year.	Declination.
1580	11° 15′ E.	1773	21 9 W.
1622	6 0 ,,	1787	23 19 ,,
1634	4 6 ,,	1795	23 57 ,,
1657	0 0 ,,	1802	24 6 ,,
1665	1 22 W.	1805	24 8 ,,
1672	2 30 ,,	1818	24 38 ,,
1692	6 0 ,,	1820	24 34 ,,
1723	14 17 ,,	1853	21 54 ,,
1748	17 40 ,,	1862	21 23 ,, (E. Walker.)

Whence it appears that the easterly declination of 1580 diminished to 0 in 1657, from which time it became more and more westerly till 1818. It then began to return towards 0, and is still doing so, though so slowly that it would be rash to predict when, or even if, 0 will be reached.

Besides this change there is a daily variation in declination of such a nature that the needle in the twenty-four hours passes twice through its mean position. Commencing shortly after midnight, the N.-seeking pole moves to the E.; at about a quarter-past seven it is 6′ or 7′ from its mean. It then travels back again, and passes the mean magnetic meridian at about ten o'clock. Still travelling westward, at about one o'clock it reaches its extreme daily westerly excursion, which may be as much as 3° from the mean. It then begins to move eastward; it passes the mean at about five or six in the afternoon, and continues slowly till about ten or eleven, probably really all night; but between ten or eleven at night and one or two in the morning the motion is insensible. The first morning movement is in the same direction as the last sensible evening motion. Further, having eliminated the secular and diurnal variations of declination, there is said to be another following the seasons, and which may be called a solsticial variation. The data are at present somewhat insufficient and, indeed, contradictory. The balance of evidence seems to show that there is an excess of declination in the months from September to March inclusive, and a defect from April to August inclusive; and that this is the case in both hemispheres.

348. Inclination or Dip in Time.—The dipping needle near London has also been examined for about three hundred years; the secular variation is shown below:—

Date.	Inclination.	Date.	Inclination.
1576	71° 50′	1801	70 36
1600	72 0	1821	70 3·4
1676	73 30	1830	69 38
1723	74 42	1838	69 17·3
1773	72 19	1854	68 31·1
1786	72 8·6	1860	68 19·2 (E. Walker.)

Hence, within historic times, the dip has increased and is diminishing. It does not appear that the date of maximum dip is that of no declination.

349. Diurnal Variation in Dip.—Taking a whole year and the mean dip at half-past twelve, which is the time of minimum, the dip at eight is 1'·6 greater. Thence it diminishes, with some fluctuation, at about 9 P.M. till midnight. But the hourly maxima are different for different months, thus:—

In Jan.	the max. is at	9	A.M.	In July	the max. is at	8	A.M.
,, Feb.	,,	7	,,	,, Aug.	,,	7	,,
,, March	,,	7	,,	,, Sept.	,,	6	,,
,, April	,,	7	,,	,, Oct.	,,	5	,,
,, May	,,	9	,,	,, Nov.	,,	5	,,
,, June	,,	9	,,	,, Dec.	,,	8	,,

350. Local Variation of Declination.—If we imagine the earth to be covered with perfectly similar declination needles without influence upon one another, we should find certain of them having no declination. The line joining all such needles is called the *Agonic* line. It may be traced from about Port Kennedy (say lat. 75° N., lon. 100° W.) through Hudson's Bay, Lake Superior, Florida, and reaching South America at about the mouth of the Amazons, it passes through Brazil, and can be traced towards the S. pole as far as 60° S. Reappearing on the other side it passes through Western Australia, strikes land again in Beloochistan, crosses the Caspian to Lapland, and thence to Spitzbergen. Besides this chief agonic line there is a remarkable closed line forming an ellipsoid between the latitudes 15° and 70° N., and lon. 105°-150° E., inclosing, therefore, Japan and parts of China, Manchouria, and Siberia. It is almost certain that there is a similar, though smaller, loop agonic line just south of the equator, and between 120° and 130° W. If we, in like manner, follow the line of needles which have all, say, 5° W. declination we pursue an *Isogonic* line; this runs nearly parallel with the agonic. But the greater the angle of declination on the isogonic, the more does it depart from parallelism with the agonic, and this whether the declination is east or west, until the isogonics cease to cross the equator. From what has been said in Art. 377 it follows that these agonic and isogonic lines are continually shifting slightly through the days and seasons, and altering through the centuries.

351. Local Variation in Dip or Inclination.—Further, if the earth were covered with dipping needles, we can imagine ourselves travelling south until we reach a needle which, instead of dipping towards the N., dips towards the S There must be some place where the needle is horizontal or tangential to the earth. Starting from this, and following the needles which are all horizontal, we pursue the *Aclinic* line, or magnetic equator. This crosses the geographic equator twice, namely in the Gulf of Guinea in lat. 10° E., thence eastward it rises to about Aden; thence it gradually sinks till it crosses the equator at about 180°, strikes South America at Ecuador; still sinking, it emerges at about Baiha in Brazil, whence it rises again to the Guinea coast. *Isogonic* lines are those along which the dip remains the same. Those along which the dip is small run pretty parallel with the magnetic equator; but, as with isoclinic lines, the greater the dip the greater the eccentricity. Isogonic lines are, however, all closed curves, diminishing in length as we approach the poles, that is, as the dip increases. At last, going say north, and crossing the isogonics, we find a needle or region of needles, pointing their N.-seeking poles, as nearly as can be measured, vertically downwards. This region may be called the N. magnetic pole of the earth. It does not coincide with the earth's geographic pole, but is situated in 70° 5′ N., and 96° 45′ W. At the magnetic pole a declination needle is, of course, at rest in any position. The S. magnetic pole has not been reached.

352. Unit of Magnetism, and Intensity of Earth's Magnetism—Magnetometer.—A unit of magnetism is usually defined as follows: a magnet is said to have a unit of free magnetism when it fulfils the following conditions:—Let it be A, and be free to turn in a horizontal plane. In that plane let there be a precisely similar and equally magnetised magnet, B, at right angles to A, and opposite its centre at a distance of 1 m.m. from it; then A has one unit of magnetism if it tries to turn round with a force equal to that which would be exerted by a force of 1 millegram acting at right angles to an arm 1 millimeter in length.

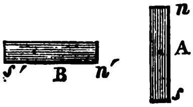


Fig. 291.

The rate at which a magnetic rod oscillates in a horizontal plane depends upon the moment of inertia of the rod, and the horizontally directive component of the earth's magnetic action upon it. The latter, again, depends upon, and is, indeed, the product of the intensity of the earth's magnetism with the magnetism of the rod. If, therefore, we have to compare the varying magnetic intensities at different times, and further to estimate the absolute magnetic force of the earth, we compare the number of oscillations which the same magnet performs in a given time; and thence deduce, in magnetic units, the earth's magnetism at those times.

More precisely, the directive magnetism of the earth acts in the magnetic dip or inclination, which we will call i. The total directive force is clearly equal to the horizontal directive force divided by the cosine of the dip

$$T = \frac{H}{\cos i}.$$

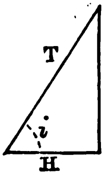


Fig. 292.

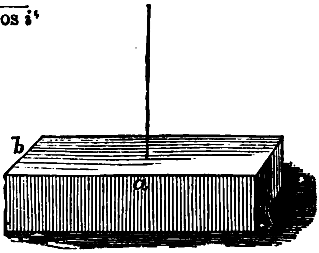


Fig. 293.

To find H, a rod needle of definite shape and weight is suspended from its centre and set vibrating; let the time of a single vibration be t. Let b, a, and w be the breadth, length, and weight of the rod; then the moment of inertia of the rod is,

$$w \times \frac{a^2 + b^2}{12}.$$

The moment of the couple which sets this mass swinging once in time t must be

$$\frac{w(a^2 + b^2)}{12gt^2}\pi^2.$$

Now t, w, a, and b are experimental data, π is a constant, and g may be assumed to be so for the same place. We get, therefore, for the moment of the couple a number (in, say, gram meter measurement). Call this m. The total moment, m, is made up by the moment due to the magnetism of the earth (e_m), and that of the rod (r_m), and $m = e_m . r_m$. To find the ratio between e_m and r_m the effect of the action of both on a needle can be determined. For if the rod under experiment is brought parallel to (and in the magnetic meridian) a needle at a distance d, the needle will be deflected through an angle θ; then (see Art. 382.),

$$\frac{r_m}{e_m} = r^3 \tan\theta;$$

whence,

$$e_m = \frac{\pi}{2}\sqrt{\frac{w \times \frac{a^2+b^2}{12}}{gd^3 \tan\theta}};$$

or the total,

$$e_m = \frac{\pi}{2\cos i}\sqrt{\frac{w(a^2+b^2)}{12gd^3 \tan\theta}}.$$

353. Total Action of a Distant Magnet.—This action can be measured by the deflection produced on a needle when the magnet is placed in the same plane with it, so that the axis of the magnet, if continued, would pass through the pivot of the needle. For small deflexions the angle itself may be taken to represent the deflecting force. If d be the distance between the pivot of the needle and the centre of the magnet, the angle varies as $\frac{1}{d^3}$; and this is the more nearly true the greater the distance. For greater deflexions this must be multiplied by $\tan\theta$; so that the directive force of the magnet which effects a certain angular displacement varies as $d^3 \tan\theta$. From these data it has been calculated that there is as much magnetism in 3 cubic feet of the earth, supposing it to be uniformly magnetic, as can be held by a steel rod weighing 1 lb. But, of course, this is far from being uniformly the case. Immense areas of sea, miles in depth, are without appreciable magnetism; while many mountain ranges show such great magnetic moment, owing, probably, to the quantity or condition of the iron compounds in them, or a little below their surface, that their conditions are quite abnormal. In places, indeed, where a ferruginous mountain rises abruptly, the magnetic needle may turn through an entire revolution as the traveller passes round it.

354. Methods of Relative Measurement.—The tendency which a magnetised needle has to set itself N and S arises from the attraction of its N.-seeking end to the N. and its S.-seeking end to the south magnetic pole. These poles may be considered to be at an infinite distance, so that the directive forces of the earth's magnetism may be supposed to act in parallel planes. If, then, a magnetised rod of steel be hung from a wire having torsion, and if it be so arranged that the wire has no twist when the magnet is N and S, the degree of twist which must be given to the upper end of the wire, in order to produce a given angular displacement in the magnet, is a measure of the magnetism. For (compare Art. 220) the amount of turning of the wire is exactly in proportion to its restorative effort toward the position of no torsion, which, when there is equilibrium, is exactly equal to the resolved part of the directive magnetism of the earth acting perpendicularly to the needle. This is equal to the total horizontal directive magnetism multiplied by the sine of the angle of deflexion, which latter for small angles may be taken at the angle of deflexion itself. At places where the dip is the same, the relative earth's magnetism may be at once deduced by measuring the angle through which the top of a given torsion wire must be turned in order to throw a bar magnet of given strength out of the magnetic meridian by a given small angle. The total directive force is of course proportional to this divided by the cosine of the angle of dip.

355. Method of Oscillations.—We may consider the N.-seeking end of a magnet to be pulled towards the N pole with exactly the same force as the S.-seeking end is pulled to the S. The two halves may be regarded as independent, but strictly isochronously pendular. The universal law of pendulum motion is that the force producing the oscillations varies as the square of the number of oscillations in a given time. If Mm be the magnetism of the magnet, and Em the whole of that of the earth, then $Em \cos i$ is the horizontal directive magnetism of the earth, and Mm Em **cos** i **is** the mutual action which determines the rate of oscillation. If a given needle therefore gives n_1 oscillation in an hour in one place, where the dip is i, and n_2 in another, where the dip is i_2, there must have the relation

$$\frac{n_1^2}{n_2^2}=\frac{M_m E'_m \cos. i_1}{M_m E''_m \cos. i_2}=\frac{E'_m \cos. i_1}{E'' \quad \cos. i_2}$$

or if $i_1=i_2$ there is the simple relation

$$\frac{E'_m}{E''_m}=\frac{n_1^2}{n_2^2}$$

356. Law of Magnetic Action at a Distance.—By counting the oscillations in a given time, the law connecting the magnetic force with the distance may be deduced. Supposing a small needle, by the action of the earth alone, gives n oscillations in one minute. Bring now a S magnetic pole of another magnet toward N at a distance d. The magnet now makes n_1 oscillations. The earth's force is represented by n^2, the force of the earth and magnet by $n_1{}^2$, so that the magnet's force is represented by $n_1{}^2-n^2$. If the magnet is moved to double the distances there may be n_2 oscillations in a minute, as before $n_2{}^2-n^2$ of these are due to the magnet alone. Accordingly

$$\frac{n_1{}^2-n^2}{n_2{}^2-n^2}$$

gives the relative magnetic forces of the same magnet at distances 1 and 2. Experiment shows that then'

$$\frac{n_1{}^2-n^2}{n_2{}^2-n^2}=\frac{1}{4}.$$

or that where the distances is doubled the magnetic force is divided by 4. Following this out it is found that for small magnets, or rather one small movable one and a long fixed one, the magnetic force, like gravity, light, and heat, varies inversely with the square of the distance.

357. Isodynamic Lines.—The intensity of the earth's magnetism can at once be measured by the rate of oscillation of a dip needle. But there are such serious practical difficulties in the way of its employment that one or other of the ways above sketched are used in preference. The line of minimum magnetic intensity is nearly identical with the magnetic equator or no dip, but lies further from the geographic equator, and cuts it in two points more nearly opposite to one another. Further from this line, in both hemispheres, the magnetism becomes stronger. The lines of equal magnetic force, or isodynamic lines, soon loose their parallelism to the minimum line, and form certainly one and probably four loop systems in the centre of which the magnetic intensities are at the maximum. Some of these regions are very near to the geographical or magnetic poles, they are all above 50° N. or S. lat. The one best examined has its centre about 50° N. lat. and 90° W. lon., that is about the south of Hudson's Bay.

358. Illustration of Earth's Magnetism.—That the earth, like other magnets, can give both permanent and temporary magnetism is shown by many natural and artificial phenomena. The permanent magnetism of lodestone, when its deposits are in the magnetic meridian, is an example of the one kind, and the magnetism in the soft iron of a dynamoecletric machine, in Art 296, is an example of the other. If a bar of soft iron A, fig. 294, is supported in the magnetic meridian and in the dip, the lower end of the bar is found to repel the N.-seeking pole of a magnet. It is the lower end which is towards the N. magnetic pole (having S.-seeking magnetism). Accordingly, the inductive action of the earth will be to make the lower end N.-seeking. On turning the bar over, so as to reverse the position of its ends, it is still the lower end which has N.-seeking magnetism. A soft steel poker held in the same position and struck will have similar but more permanent poles developed in it; these are also reversable on inverting the poker and rehammering it. If a cylinder of soft iron is placed in a coil, whose ends are connected with a galvanometer, and the axis of the whole is in the magnetic meridian,

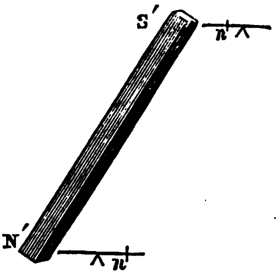


Fig. 294.

the very act of putting the cylinder in and taking it out will cause a deflexion of the needle. The effect is much increased if the coil and cylinder are turned over, so that the induced magnetism in the iron may be reversed.

359. Magnetism of Iron Ships.—The riveting and other hammering during the building of an iron or iron-plated ship will, if the ship lie in the magnetic meridian, give rise to a large amount of permanent magnetism so as to interfere with the action of the compass. Even when the ship lies magnetically, east and west, during its construction many of the pieces must lie in or approximately in the magnetic meridian, and acquire permanent magnetism. A part of this is subsequently lost by the buffeting of the waves when the ship is in various attitudes. The induced magnetism from the earth is a serious element, for it causes the needle to follow the ship. Lightning may, of course, completely alter the magnetic condition. It is usual to swing the ship, and compare the true bearing of some distant object with the compass bearing. This has to be done whenever it is suspected that by movement of the anchors, armament, etc., the magnetism has been altered. Sometimes a mass of iron is temporally fixed near the compass in such a position, determined by trial, as to counteract the ship's magnetic action. Sometimes a fixed magnet is used for the same purpose. In many vessels, one compass at least is placed as far aloft as convenient for occasional reference. The earth's induced magnetism not only varies with the varying earth's magnetic intensity, but, of course, with the bearing of the vessel and with its rolling, and, to some extent, with its pitching.

CHAPTER III.

DISTRIBUTION, POLES, CURVES, EFFECT OF HEAT.

360. In Art 336 it was shown how the fragments of a broken magnet are themselves perfect magnets. They were mentioned as being not less strong than the original. If we examine the central fragments we find their polarity stronger than the extremes. Yet when they are joined together it is only near the ends that free magnetism is appreciable. If the polarity of the elements were equal, we should get attraction only at the poles. Thus, fig. 295 (1), let the six elements each have the polarity represented arbitrarily by 10, and let all the numbers above represent N.-seeking poles, and those below S.-seeking poles. The intermediate equal and opposite polarities neutralise one another, so that we have (2) a N.-seeking pole at one end and a S.-seeking pole at the other, and no intermediate magnetism. This is not

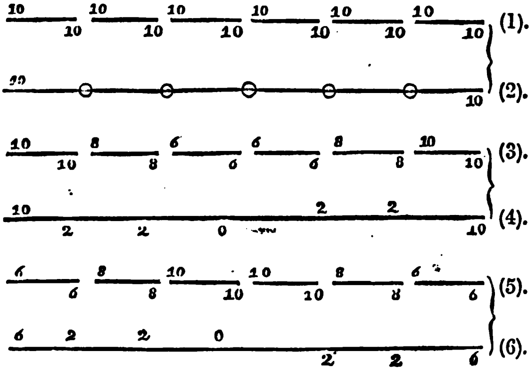


Fig. 295.

the case, and, consequently, the magnetization of the elements cannot be equal. Secondly, (3) let the elements get more strongly magnetic towards the ends. The opposite touching poles of the elements would not neutralise one another. But (4) we should have the impossible condition of the whole of each half of the bar having one polarity, excepting at the end where it is reversed. If (5) the elements are strongest in the middle, we have some magnetism of one kind on each half, terminating by a large amount of the same kind at the end (6).

361. Distribution.—A very long magnet is placed vertically. The time of oscillation of a short magnet, under the influence of the earth alone, having been found, the short magnet is brought within a certain distance of the centre of the vertical one. Its rate of oscillation is found to be identical with that caused by the earth only. The central part shows no attraction. If it be moved vertically downwards, being kept at the same distance from the vertical and also in the magnetic meridian, it is found to oscillate more rapidly as its stations approach the end. And the same increase of rate occurs if it be placed on the other side of the vertical, along its upper half. Squaring the number of vibrations in each case, and subtracting from each square the square of the earth's vibrations, we get numbers representing the magnetic intensity along the magnet. This is found to be greatest at the ends, and to diminish, at first rapidly, and then more slowly, towards the centre, in such a fashion that, if equal abscissae are taken along the magnet, the ordinates representing the magnetism trace out a curve such as is shown in fig. 296 (1), where the N polarity is represented by ordinates above, and the S by ordinates below the magnet.

362. Poles.—This being the distribution of the free magnetism, let us consider briefly the behaviour of north magnetic element *n* towards the magnet, N S, fig. 296 (2). The lines drawn from *n* represent the magnetic repulsions of the one half, and the attractions of the other. These lines, to represent the amount of the forces, must depend upon the *length* of the ordinates of fig. 296, and also upon the *distances;* since, Art. 356, the attraction (and repulsion) vary *inversely* as the square of the distances. We may continue these lines above the N end, so as to represent the respective repulsive forces, and cut off portions on the S end to represent the respective attractive forces. The resultant of each set will lie amongst them; and the points where these resultants cut the magnet are the poles of the magnet for that particular point, *n*. P*n* is the point from which *n* would move if the N half only existed. P*s* is the point to which *n* would move if the S half only existed. At a finite distance from a magnet, therefore, the poles vary in position according to the place of the affected body. At a considerable distance, where the lines of attraction and repulsion may be all considered

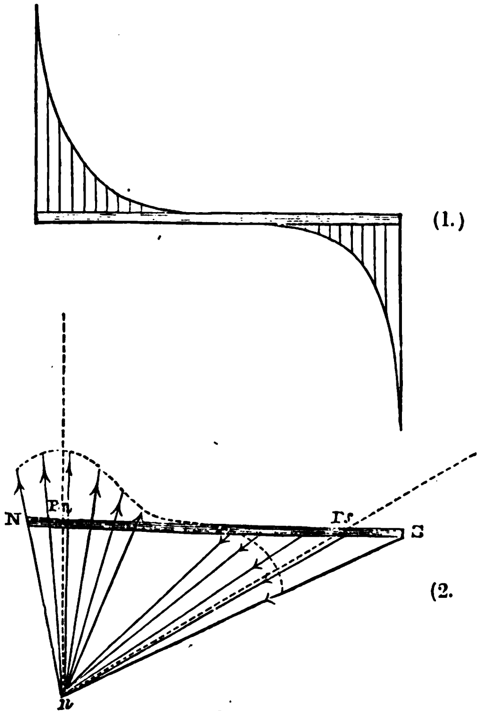


Fig. 296.

parallel, and where the distances may all be considered equal, the ordinates of the fig. 296 (1) represents the relative magnitudes of the acting magnetic forces. The resultant on each side passes through the centre of gravity of the corresponding plane figure. And the points where these resultants cut the magnet are what may be called, borrowing an optical expression, the principal poles, or poles for parallel magnetic rays. The principal poles may be considered to lie about $\frac{1}{6}$ of the magnet's length from each end.

363. Magnetic Curves.—The region within which a magnet is exerting its force is called the magnetic field. The attitude which a small elementary magnet, either permanent or induced by the action of the fixed magnet, assumes depends upon its relative distance from the two poles. Suppose, fig. 297 (1), we have an N and S pole of, say, a horse-shoe magnet, N and S. Let there be a little elementary magnet, *n s*, represented by a dot in a circle, twice as far from S as it is from N. If the force with which *s* is repelled from S is 1, then *s* will be attracted to N with a force 4. Similarly, *n* being attracted to S with a force of 1, will be repelled from N with a force 4. Drawing lines in these directions of these relative lengths, we get two similar parallelograms whose diagonals are in a straight line. The *n* will be repelled along the upper diagonal, and the *s* attracted down the lower one; the needle will therefore come to rest in this diagonal. If, instead of an N and S pole, we have two N poles or two S poles (2), the needle, by similar reasoning, rests as in the figure (2). In the first case the prolongation of the needle will not pass between the poles; in the second it will. The *positions* of the elementary magnets are seen well on placing

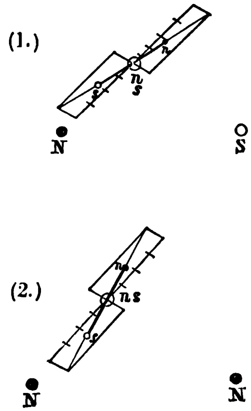


Fig. 297.

a shallow tambourine of white paper over a magnet or pair of magnets, and strewing fine iron filings or dust upon the paper. On tapping the paper the filings arrange themselves in curves. Fig. 298 (1) shows the arrangement with a single magnet; (2) a horse-shoe magnet; (3) a pair of bar magnets, arranged N to S; (4) the same, N to N and S to S.

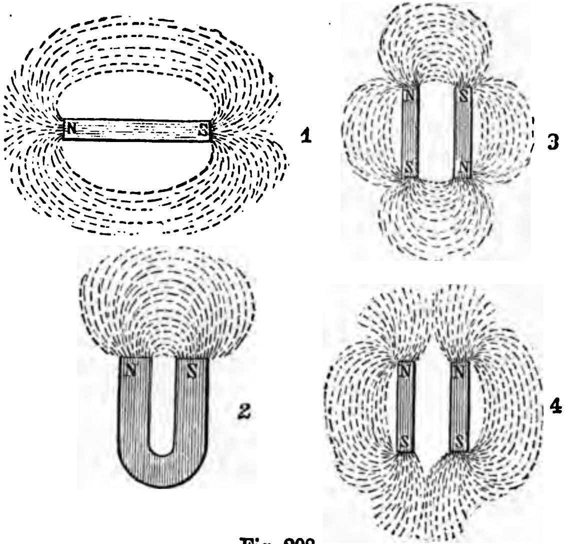


Fig. 298.

These magnetic curves can be rendered permanent by using glass to receive the filings, and then pressing upon the glass paper moistened with gum and a solution of nut galls, which enables the filings to print themselves, so that, when they are shaken off, their stains remain. Each of these elementary magnets is a tangent to a curve, which is called the magnetic curve, or line of magnetic force.

Considering the earth as a magnet having only two poles, the lines of magnetic force are lines in vertical planes parallel with the dipping needle. An idea may be got by likening them to a shower of rain falling due towards the magnetic north with an inclination of about 68°. Of course, it is only a figure of speech to call these lines. There are no actual lines present. It would be fitter to compare the field to a region of varying tension or even density, and to look upon the arrangement of the iron particles as being due to the structural density of the magnetic influence. Again, these lines are like planes of cleavage, which do not exist in an unbroken mineral.

364. Effect of Heat on Magnetism.—It was shown in Arts. 90, 91, that heat discharges electricity; that a white-hot iron ball cannot receive a charge; that even at a lower temperature it cannot receive a + charge, and that it discharges another body by induction by releasing the + electricity which the electrified body develops in it. Further, in Art. 301, it was shown how heat obstructed the galvanic current. Considering the closely related nature, to say the least of it, of electricity and magnetism, we should expect heat to stand in relationship with magnetism. The principal results of experiments in this direction may be briefly summarised as follows: A magnet, whether saturated or not with magnetism, becomes less magnetic when heated even only a few degrees centigrade. Hence the difficulty in using the magnetometer and similar instruments. On cooling, the magnet recovers apparently all its magnetism. A magnet heated to 100° not only is less magnetic when hot, but fails to recover, as it cools, a great portion of what it lost. Heated to 200°, it loses permanently more, and so on. The magnetism losable at a given temperature is not, at least for lower temperatures, all lost as soon as that temperature is reached. A magnet may be continually losing irrecoverable magnetism during the whole of an hour that it is being boiled in water. A magnet, partially saturated at 60° C., loses magnetism not only by being heated but by being cooled. A steel magnet loses the whole of its magnetism when heated to a bright red; and iron at this temperature is not attracted by the magnet. The temperature at which iron ceases to be attracted (and the temperature is pretty sharply defined), is close to that at which it refuses to hold a charge of electricity.

The metal cobalt, though much less strongly magnetic than iron, retains its magnetism at a much higher temperature.

CHAPTER IV.

DIAMAGNETISM AND RELATION TO RADIATION.

365. All substances appear to be either attracted or repelled by the magnet. Iron, nickel, cobalt, chromium, manganese, titanium, cerium, palladium, platinum, and osmium are magnetic, or attracted by a magnet. The metals bismuth, antimony, lead, tin, mercury, gold, silver, zinc, and copper are repelled by magnets, as also are the non-metallic substances, water, alcohol, phosphorus, sulphur, sugar, and starch. Bodies which are repelled are called diamagnetic, in distinction from magnetic or paramagnetic. A bar of a magnetic substance placed between two unlike magnetic poles, will set itself lengthways, pointing from pole to pole; hence its attitude is called axial. A bar of a diamagnetic body will set itself at right angles to this position in its endeavour to get as far away from the poles as it can. Its position being perpendicular to the axial is called equatorial.

366. Pseudo-diamagnetism.—If we were to conclude that a substance is diamagnetic because a rod of it sets itself equatorially we should incur serious error, because not only the nature, but the structure also, influences its attitude. Thus a series of short iron wires, laid side by side on a cake of wax, so as to form a band four or five times as long as it is broad, that is, as the length of each wire, may be floated in a dish of water above the poles of a magnet. The axial attitude taken up by each elementary wire compels the whole iron band to set itself equatorially, which it accordingly does. Each of a number of circular discs of iron plate, when hung by the edge, sets axially. But if they are clamped together so as to form a continuous rod, this rod, though consisting wholly of iron, will act like a diamagnetic body, and rest equatorially. Such structure may be given to a body by pressure, for pressure tends to develop lamination perpendicular to itself. Thus, powdered carbonate of iron, which is strongly magnetic, will, if mixed into a paste with gum and strongly squeezed, give a disc which, when hung from the edge, sets equatorially. Bismuth powder, which is the most diamagnetic of all substances, will, when similarly treated, set axially.

Another point to be noticed is the influence of the medium in which the manifestation takes place. Thus, a weak solution of sulphate of iron will, when hung in the air in a glass tube, stand axially. If it be hung in a stronger solution it will stand equatorially; not, of course, through diamagnetism, but through what may be called magnetic buoyancy, that is, through the superior magnetism of the medium. This source of error may be misleading in examining gases. None of the gases are sufficiently magnetic to seriously influence the apparent magnetism and diamagnetism of solids and liquids.

367. True Diamagnetism may be exhibited by hanging a bar of bismuth, free from iron, between the poles of a strong electro-magnet by means of a long thread of cocoon silk. On exciting the magnet it swings, and finally becomes equatorial. A pellet of bismuth will be repelled a tenth of an inch from the pointed pole of an electro-magnet, if hung by a long silk fibre, so as just to rest against it. The flat pointed poles of a strong electro-magnet are covered with a very thin sheet of glass, upon which very fine bismuth powder is scattered, on tapping, the bismuth is repelled as shown in fig. 299. No trace of linear structure is to be seen as we perhaps might expect, under the assumption that the particles are capable of diamagnetic polarity; for if this were the case to any appreciable *extent* we should get a family of curves at right angles to

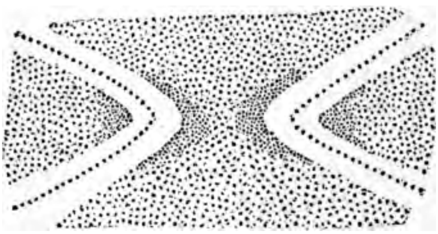


Fig. 299.

the magnetic curves. That such polarity can be given, and that, under like circumstances, it is the reverse of that which iron would assume, appears from the following experiment. Fig. 300, *ab* is a bar of pure bismuth swinging horizontally and freely in the inside of a copper coil C. Opposite to the ends of *a* and *b*, also in a horizontal plane, are the four poles of electro-magnets D,E,F,G. If around C such a current is sent as would make *a* a N.-seeking pole if it were of iron, and at the same time currents are sent through D and G, such as to make *d* a S.-seeking and *g* a N.-seeking pole, the bar of bismuth instead of turning *a* towards *d* and *b* towards *g*, as would be the case with iron, turns in the opposite direction, and this opposite motion is assisted if *e* be made N.-seeking and *f* a S.-seeking pole. The bismuth acquires the opposite polarity to that which an iron bar would get by the same current.

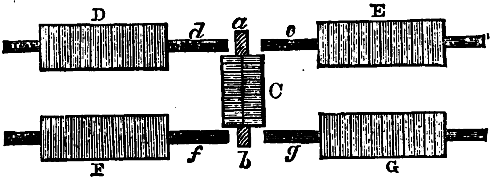


Fig. 300.

Crystalline bodies which exhibit sensible amounts of diamagnetism or paramagnetism do not do so equally in all directions, that is, unless cubical, they have directions of greatest inductive capability, and it is these directions which set themselves axially or equatorially, and so determine the position of the crystal which, in its general figure, may be at right angles to this direction as in the artificial cases, Art. 366.

368. Magnetism and Diamagnetism of Gases.—If a gas be allowed to stream between the poles of a magnet, it will spread itself out axially or equatorially according as it is paramagnetic or diamagnetic. The motion of the gas can be manifested by making it pass in succession through hydrochloric acid and over liquid ammonia. It thus becomes charged with clouds of chloride of ammonium, which make it visible.

Another method consists in arranging three vertical tubes above the gas delivery tube, one directly above it, one in equatorial plane, and one in the axial plane. In each of these is a piece of blotting paper wetted with ammonia, while a similar piece, wetted with hydrochloric acid, is in the lower tube, according as the gas is magnetic or diamagnetic relatively to the air. These experiments do not prove either the actual magnetism or actual diamagnetism of any of the gases. The gases may be all magnetic, and differ only in degree, or all diamagnetic and differ only in degree. Oxygen is the only gas which is more magnetic (or less diamagnetic) than air (therefore than nitrogen). It is the most magnetic (or least diamagnetic) of all gases. The following gases are found diamagnetic to air (or less magnetic), N, H, CO_2, C_2O_2, N_2O, C_2H_4, HCe, HI, NH_3, I, Cl, Br, CN.

369. Effect on Polarised Light.—Although the induced current only runs when change in the primary or in the position between the two takes place, it has been suggested that the secondary wire, when no such change is occurring, is in a condition to which the term electrotonic has been given. Similarly, it is supposed that the magnetic field pervades and influences all bodies in it, although that influence may not manifest itself as magnetic induction. This appears to be the case; and since, as will be shown immediately, the condition of the field is betrayed by its influence on light, it is not unlikely that magnetism and light may be influences on a common medium.

A beam of light, when sent through a Nicol's prism, emerges as plane polarised light, that is, its undulations are all in one plane, or rather parallel planes, say parallel to the plane of the paper. If a similar Nicol prism is so placed as to polarise a beam of light in the same plane as the first, then light, after passing through the first, will pass through the second without obstruction. If the second be turned on its axis through a right angle, the light polarised by the first prism will be totally obstructed by the second, the surface beyond the second will be in darkness, unless the plane of polarization of the light which has *passed* through the first prism is turned before it reaches the second. If it be turned in this interval through 90°, it will strike the second prism in undulations parallel to these which the second is competent to transmit, and the space beyond becomes luminous. In intermediate degrees of twisting only portions of the light pass through. This turning of the plane of polarization of polarised light takes place in the magnetic field when the plane polarised light is passing through certain substances, solids and liquids. Among solids the one which shows this property in the most marked manner is "heavy glass," a silicate and borate of lead. The experiment is shown in fig. 301. Two armatures, *a* and *b*, have horizontal holes through them, and rest upon the possible electro-magnet. With its ends entering these holes is a rod G of heavy glass, having its ends vertical and polished. The light from the source C passes through the prism N, which we may suppose to polarise it in the plane of the paper. It then traverses the glass G, and reaches the Nicol N_2, whose plane of polarization is represented at right angles to that of N. If the magnet be not excited no light passes through N_2; but when excited, so that one pole is S. and the other N., the hitherto dark field becomes luminous. If the current round the magnet is reversed, the field becomes and remains equally luminous. The plane of the light polarised by N has been turned by the magnetic influence, and some of it is able to pass through N_2, somewhat in the

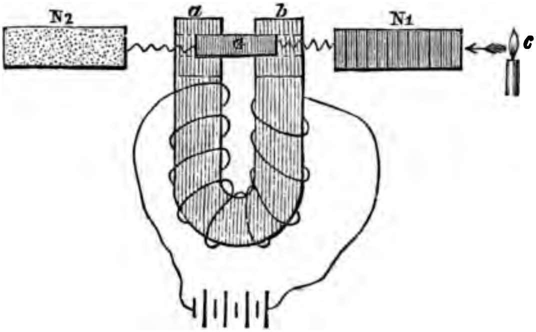


Fig. 301.

same manner as though a sheet of mica had been interposed. But there is a very important essential difference which must be insisted on. It is clear that the currents which circulate around the glass are all in one direction if the poles are opposite. It also appears from experiment that if the body be laid in the axis of a coil, through which a current is made to pass, it then also turns the plane of the polarised light which it receives. To find in which direction and how much the plane has been turned, we have to find in which direction and how much the second Nicol must be turned to restore the dark field. It is found that the Nicol has to be turned in all cases in the direction of the current. In other words, the current appears to drag the plane of polarization with it. Accordingly, if we looked at polarised light coming through the magnetically influenced glass we find it turned in a right or left-handed manner, according as it emerges from the south or north-seeking end of the helix. A body which polarises circularly, like dextrine, always turns the plane to the right, while lœvo-polarises always turn it to the left, in whichever direction the light passes through them.

The angle through which the plane of polarization is turned is directly proportional to the current strength, and increases with the refractive index of the substance: at least when they are both solids or both liquids. The following is a comparison between a few substances :—

Heavy Glass,	6°
Bisulphide of Carbon,	3
Flint Glass,	2·8
Rock Salt,	2·2
Water,	1·
Strong Solution of $FeCl_2$	0·3

which shows that the effect is not proportional to the magnetizability of the body, but is connected rather with what is sometimes called in optics the density or tension of the æther. If anything, experiments seem to show that solutions of diamagnetic metals turn the polarization plane more, and those of magnetic metals less, than does water.

APPENDIX (A).

I. To make shell-lac varnish, the lac should be just covered with alcohol, or methylated spirit, and left for twenty-four hours, with occasional shaking. The clear is poured off, and the undissolved treated with a little more spirit.

II. Films of collodion are best made from the least highly nitrogenised gun-cotton. The collodion is poured into a clean flask, which is turned round, inverted and drained. When dry, a quill is put down the neck, and the edge of the collodion film twisted upon it: this allows the air to escape as the balloon of collodion leaves the glass. Such balloons, when fractured, serve for electric experiments.

III. Amalgam for electricity: Melt in an iron ladle 1 oz. of tin; add gradually 1 oz. of zinc in scraps; thoroughly mix with an iron stirrer; allow to cool till solidification begins; remelt, and add 2 oz. of hot mercury. Stir; throw into a warm iron mortar and stir up with an iron pestle till cold. Keep in stoppered bottle. When used the amalgam should be stirred up with a very little lard, which has been well washed and dried.

IV. To make glass caps, a hard Bohemian tube is drawn out and the end closed, and so rounded that the inside is quite a smooth curve. This is cut off, giving a piece about ½ inch long.

V. To make a balanced glass tube. See Appendix B, 1 (*b*).

VI. Gold leaf is cut by placing it on a flat clean leather pad, pressing it very gently, and sawing with a perfectly straight-edged clean knife or split cane. The best Dutch metal may replace the gold leaf if perfectly smooth. The Dutch metal may be cut between paper by close shearing scissors, with such long blades that each cut is made with one motion.

VII. Soft wax. Ordinary beeswax melted and mixed with turpentine, about 10 of wax to 1 of turpentine by weight.

VIII. To cover a sphere with tin-foil, the foil is cut into gores so as slightly to ovrelap. The very thickest paste is used. Each gore is rubbed with the thumb nail, or the side of a test tube, until it lies quite smooth. This the plasticity of the tin permits.

IX. To make the cake for an electrophoros, one part by weight of wax may be melted in a pan, and five parts of shell-lac gradually added, with increased heat. Another recipe is a mixture of five of shell-lac, five of gum mastic, two of Venetian turpentine, and one of marine glue. If, after casting, bubbles appear on the surface, they may be brushed over with the flame of an air-gas burner, which breaks them.

X. Mercury is made to adhere to any metal by putting a very little sodium with the mercury, the hundredth part by weight is ample. The sodium mercury may, if necessary, be washed off by fresh pure mercury, which continues to adhere.

APPENDIX (B).

Perhaps the following hints may be useful to those who, on beginning to study electricity, are desirous of making for themselves, and using to illustrate principles, some of the apparatus described in this book. The notes were issued last year to my laboratory students; and have been suggested in a very great measure by those gentlemen who have now and again given me the benefit of their experience in conducting the laboratory work:—

1. (*a.*) **A Glass Tube for electric excitation.**—Glass tube about 18 inches × ¾ inch. Thoroughly clean and dry the inside (this is very important), close and round one end, fuse edges of the other end.

(*b.*) **Balanced Glass Tube.**—Glass tube about 12 inches × ¾ inch. Clean and dry the inside, close and round one end, nearly close the other end. Balance on the edge of a knife, mark the centre with ink. Soften one side of the tube at centre in air burner, push in side with a point so as to make a conical cap.

(*c.*) **Attach Insulating Threads to some Pith Balls.**—Cut balls roughly to shape with a knife, finish with a file or glass paper. Thoroughly dry and warm silk thread, while warm immerse in melted paraffin. Wipe off as much paraffin as possible. Attach to pith ball.

(*d.*) **Proof-Plane.** — Circular disc of gilt paper about 2 inches diameter, fastened on end of strip of varnished glass.

2. **An Electrified Body attracts and is attracted by Unelectrified Bodies.** — Glass tube rubbed with silk, sealing-wax rubbed with flannel, hot brown paper rubbed with clothes brush, and paraffined paper rubbed with fingers, all attract light bodies; the excited paper adheres to wall, paper and excited balanced tube are attracted by hand.

3. **Show the existence of two Electricities.**—Suspended pith ball, when repelled by excited glass, is attracted by excited sealing-wax, and *vice versa.* Two excited glass rods repel each other, two excited shell-lac rods also repel each other, but excited glass attracts excited *shell-lac.*

4. **Make a Gold-leaf Electroscope.**—Clean and dry glass flask, fit with cork, bore cork and fit with piece glass tube about 1 inch long. Cut zinc disc 1½ inch diameter (or use a penny piece), drill and solder to it a straight brass wire 9 inches long. Drill hole in edge of disc. Fill tube, previously cleaned and warmed, with clean shell-lac (or mixture of shell-lac and common resin), warm wire and push through. The efficiency of the instrument depends on insulation by shell-lac, great care must therefore be taken to get rid of all dirt or moisture. Fix glass tube in cork, varnish outside of glass. Clean wire and bend lower end round into a hook, horizontal part being about ⅜ inch long and flattened to receive gold leaves. Cut two strips of Dutch metal, say 3 inches × ½ inch wide. Gum each side of hook and take up leaves. Shade from air currents and place in flask.

5. **Test insulating power of Metal, Wood, Twine, Silk, Sealing-wax, Glass, Paraffin, etc.**—Charge electroscope, connect one end of substance with earth, bring other end into contact with cap of electroscope; note time in which electroscope loses its charge in each case. Note difference between substance used in its ordinary condition and same substance carefully dried.

6. **Excite conducting Bodies and determine quality of Electricity.**—Hold end of wood or metal rod in piece of vulcanised India-rubber sheet, excite rod by rubbing with fur or India-rubber; test kind of electricity on rod.

7. **Show that Rubber is excited with opposite Electricity to that of Body rubbed.**—Make small proof-plane with flannel instead of gilt paper, rub sealing-wax or gilt paper carrier with the insulated flannel; test kind of electricity on each.

8. **Show that kind of Electricity depends on Rubber.**—(*a*) Rub sealing-wax with flannel and with gun cotton. (*b*) Rub brown paper with India-rubber, with flannel, and with brush. (*c*) Rub ebonite with silk and with amalgamed silk. Test kind of electricity developed in each case.

9. **Make Spherical, Cylindrical, and Conical Conductors.**—Coat wood ball with gilt paper or tin-foil, and attach paraffined silk thread. Make cardboard tube about 6 inches long, covered with gilt paper, and of such diameter that the ball just fits into it, and forms spherical end. Make gilt cardboard cone about 6 inches long, to fit ball in similar way. Silk threads are to be attached to cylinder and cone for suspending them.

10. **Determine Relative Distribution of Electricity on various parts of Surfaces of above Conductors.**—Insulate and charge conductor. Test with small proof-plane and electroscope.

11. **Show that a Point discharges Electricity.**—Attach fine sewing needle to insulated conductor, charge conductor by glass rod and proof-plane. Test condition by proof-plane and electroscope. Repeat experiment without the point.

12. **Examine Condition of Insulated Ball under Induction.**—Suspend

ball, bring excited glass near, examine near and distant sides of ball with carrier and electroscope.

13. Charge Insulated Conductor with Negative Electricity by Induction.—Bring excited glass near, touch conductor with finger, remove finger, then remove glass. Test electricity. Ascertain whether the part of the ball at which it is touched makes any difference as to quality of electricity which remains.

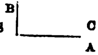
14. Charge Electroscope by Glass Rod (*a*) with Negative, (*b*) with Positive Electricity.—(*a*) Charge by induction as in No. 5. (*b*) Charge by conduction with proof-plane. Test quality in each case.

15. Show that Electricity is found only on the Exterior of a hollow Body.—Suspend hat by insulating threads, charge with glass rod and large proof-plane, or by induction. Test inside and outside with proof-plane and electroscope. Note large accumulation found round edges.

16. Prove that Result found in No. 1 arises from Induction by surrounding Bodies.—Test condition of table, &c., near charged hat. Place large conducting ball, earth connected, inside of hat but not touching it. Now test inside and outside of hat.

17. Make Insulating Plate.—Glass plate 10 inches × 8 inches. Thoroughly clean, warm and varnish with shell-lac on both sides Attach silk loops as handles.

18. Arrange and Illustrate Action of a Condenser.—Lay piece of tin-foil 7½ inches × 6 inches, earth connected, on table, on this lay insulating plate (No. 3), and on plate a second sheet of foil connected by wire to electroscope. Charge upper foil with proof-plane until leaves just begin to diverge; cautiously lift plate and upper foil. Repeat experiment, lower foil being insulated.

19. Construct and use a Bennett's Multiplying Condenser. — Cut three sheet zinc circular discs, each about 3 inches diameter, round and smooth edges, and fit each with varnished glass handle (like an electrophorus plate). On other side of one disc (A) drop three little spots of sealing-wax. Fix handle of this disc in wood block, so that disc is insulated with spotted side uppermost. Connect it by wire with electroscope. Now give A a very small charge of electricity. Lay B on A and momentarily touch B. Remove B, lay C on A, and momentarily touch C. Place B in contact with C thus 

and momentarily touch A. Remove B, then C. Place B on A and momentarily touch B. Place C in contact with B, momentarily touch A, and so on, repeating operations ten or twelve times. In this way a charge far too small to affect gold leaves may be multiplied to any extent.

20. Make a Leyden Jar with Movable Coats.—Paste piece of tin-foil or metallic paper, 8 inches × 15 inches, on card. Clean and dry glass jar. Cut tin-foiled card into two strips 4 inches wide, and cut off from each strip length fully sufficient to go round jar. Make outside and inside cylinders, using surplus pieces for bottoms. Cut two strips of tin-foiled card 3½ inches x 1 inch, bend ends and paste across top and near bottom of inside cylinder at right angles to each other. Cast lead bullet on brass wire 9 inches long; pass wire through upper cross-piece of card, and attach to lower cross-piece by a cork. Clean, warm, and varnish outer exposed surface of jar.

21. **Make a Simple Discharger.**—Cast lead bullets on ends of piece of stout brass wire about 6 inches long; solder piece of brass tube ¾ inch long to middle of wire. Fix glass handle in tube with shell-lac or resin.

22. **Charge and Discharge Jar,**—Outer coating being connected with earth, charge knob with glass rod and carrier; use discharger.

23. **Investigate Process of Charging Jar.**—Insulate jar, charge knob with positive electricity, and test outer coat; the repelled positive will be found upon it. Connect outer coat momentarily with earth, then connect knob with earth, and test outer coat; a free charge of negative will be found. Remove free negative charge and test knob; it will have a free positive charge.

24. **Show that the Charge given to Jar is merely Distributed by Coatings to outer and inner Surfaces of Glass.**—Charge jar, remove and test coatings, replace, and discharge.

25. **Charge Jar Negatively from Positive Source.**—Insulate jar, connect inner coat with earth, charge outer coat. Insulate inner, and uninsulate outer coat. Test knob for free negative charge.

26. **Gradually discharge Positively and Negatively charged Jars by Pith Ball Carrier.**—Place knobs of jars 5 or 6 inches apart, suspend insulated pith ball between. The ball will oscillate between the knobs, gradually neutralising the electricity of one with that of the other.

27. **Make a Quadrant Electrometer.**—Circular disc of glass 5 inches diameter with 1 inch circular hole in centre. On one side of this fasten with gum four tin-foil quadrants, leaving ⅛ inch space between edges of quadrants and between quadrants and inner and outer edges of glass. Connect opposite quadrants by slips of tin-foil or fine copper wire passing underneath. Thoroughly clean, warm, and varnish uncovered portions of glass. Support it on four pieces of stout barometer tube, each about 3 inches long, fixed vertically in circular disc of wood. Each pair of quadrants is to be connected by wire with insulated knob on wood base; the connecting wires may pass down two of the supporting tubes. The glass disc may be fastened on tops of tubes with shell-lac, or a short piece of brass wire may be cemented into top of tube, projecting slightly so that a shoulder is formed on which edge of disc may rest. Make light flat needle of thin gilt card, zinc-foil, or aluminium, 4 inches long, with rounded ends, narrow at middle (somewhat like a dumb-bell). At right angles to centre of needle, fix stouter slip of card or metal about ⅛ inch wide x ¾ inch long; to upper end of this a fine silk fibre is to be

attached, and on it at right angles to axis of needle a mirror of microscope glass about ⅝ inch diameter is to be fixed. A small piece of magnetised steel is to be cemented on back of mirror. To lower side of needle, and in metallic connection with it, a very fine platinum wire, about 2 inches long, is to be attached. On centre of wood base, under glass disc, is to be placed a glass vessel about 1½ inch high × 2 to 3 inches diameter, containing strong sulphuric acid, the outer surface of glass being coated with tin-foil so as to form a Leyden jar. The tin-foil must be connected with earth, and a wire with platinum end dipping into the acid, and leading to an insulated knob, will serve to charge the jar. The needle is to be suspended by silk fibre from varnished glass stem, so that it swings over quadrants, as near to them as possible, without touching, the platinum wire dipping into the sulphuric acid. To use the instrument: the Leyden jar is to be charged, the knob of one pair of quadrants connected to earth, and the charge of electricity communicated to knob of the other pair. The needle must of course swing, so that its axis is over dividing line between pairs of quadrants. Small motions of the needle are rendered visible by throwing on the mirror a small beam of light, which is reflected by it to a graduated white screen at some distance.

28. Magnetise Sewing Needle by Discharge of Jar through Coil of Wire.—Make a small coil of wire on end of glass tube; cover with shell-lac. Place needle within, and discharge jar through coil of wire. Note direction of current through coil, and consequent polarity of needle. Ascertain poles of needle by floating it on water. Suspend needle by fine thread from centre, and keep for use.

29. Magnetise Soft Iron Wire with Voltaic Current, and compare results with No. 1.—Connect copper plate to end of wire coil, previously connected with positive coat of jar and zinc plate to other end. Immerse plates in dilute acid, and place iron wire in coil. Test its polarity with suspended magnetised sewing needle.

30. Examine action of Current on Magnetic Needle.—Place zinc and copper plates in dilute acid, connect by copper wire. Place suspended needle above, below, and on each side of wire. Observe deflection in each case. Placing zinc and copper plates at sufficient distance apart, examine direction of current through the liquid.

31. Make Astatic Galvanometer.—Wind about 50 feet of fine covered copper wire on wood block; remove wood; secure coil by tying with thread; insulate and stiffen coil by soaking with melted paraffin or shell-lac varnish. Make another similar coil: fix the two coils side by side on round wood block, leaving about ¼ inch space between them, and soldering two of the free ends of coils together so as to make one continuous coil. Solder other two ends of wire to binding screws, fixed about ½ inch from edge of block. Lead ends of the wire also into two little hollows cut in wood block by side of binding screws, so that these depressions may serve as mercury cups: they are convenient for shunting the galvanometer. Bend stout brass wire into flat top arch, and fix firmly in block; the straight portion of wire at top of arch having upon it a cork roller for raising or lowering needles. Magnetise two sewing needles, and fix (with opposite poles adjoining) ½ inch apart, by means of twisted fine copper wire. On same axis, ¼ inch above upper needle, fix glass, thread about 4 inches long, to serve as pointer. Suspend needles by silk fibre, and attach fibre to cork roller. Cut card into circle, 4 inches diameter, and graduate circumference into degrees. Place (but do not fix) card in proper position over coil, supporting it on two corks cemented to board. Make needles as far as possible astatic. Place them in position, and cover all with glass shade.

32. Test Delicacy and determine Zero of Galvanometer. — Solder wires to ends of a pin and a needle, join up to galvanometer, push couple through cork, so as to expose ½ inch of each metal. Dip into water and note deflection. If necessary, dissolve some salt in the water, or acidulate it, or if deflection too great shunt the galvanometer. Reverse current, and again note deflection. Repeat once or twice. Take mean of difference of deflections, and move zero of card accordingly. Now fix card in position.

33. Make a Daniell's Cell. — The materials to be used are:—The glass vessel used for Leyden jar, porous cell 4½ inches × 1¾ inches, zinc plate 8 inches × 5 inches, copper strip 4¾ inches × 1½ inches, two binding screws, copper wire, large bung which fits glass jar. Bend zinc into cylinder, 3 inches diameter × 5 inches high, attach it firmly to the bung by means of one or more pieces of copper wire soldered to zinc, and passing up through bung, connect zinc also by soldering with binding screw fixed on upper side of bung. Similarly secure copper strip to the other binding screw fixed on centre of bung. Place porous cell in glass jar, nearly fill porous cell with saturated solution of cupric sulphate, and fill outer jar to same level with dilute solution of zinc sulphate. Place plates and cover in position. Connect binding screws by short piece of wire, and test existence of current in the wire by magnetised sewing needle.

Note—The bottom of glass jar not being flat, and jar being too deep, put some clean sand in bottom for porous cell to stand upon. It will improve porous cell if bottom and ¼ inch of edge be soaked with paraffin. Put solutions back into bottles, and wash plates of your cell every day when done with.

34. Make a Wheatstone's Bridge.—Board 2 feet by 4 inches, two strips of copper 3 inches by ½ inch, and one strip 15 inches by ½ inch. Solder one end of copper wire to centre of each strip, using wires 30 inches and 10 inches for short strips, and 15 inches for long one. Fix short strips of copper at right angles to board, and 1½ inch from each end; lead wires under board and up through one end, leaving loose ends to join to galvanometer. Fix long strip on board ¼ inch from edge, lead wire from it under board to binding screw at far end. Solder a stretched German silver wire to short copper strips. Under German silver wire fix a paper scale same length as wire, and carefully divided into 100 equal parts. (It will be useful to subdivide these into 5; if the scale be ½ metre long, the large divisions will be ½ centimetres, and the small ones millimetres). Solder binding screw on each end of long copper strip, and on adjoining end of each short strip.

35. Measure relative Resistances of different Lengths of the same Copper Wire by Wheatstone's Bridge.—Insert two different lengths A and B, of the same wire, in the two gaps of bridge, join end wires of bridge to galvanometer, attach one wire of your cell to middle binding screw of bridge, and lightly touch German silver wire with extremity of other cell wire. Find place on divided German silver wire where such contact causes no deflection of galvanometer. Then the lengths of the two portions of the German silver wire are in the same proportion to each other as the resistance of A and B.

36. Find Lengths of Copper Wires by measuring their relative Resistances, the Length of one of the Wires being known.—Measure relative resistances as above; the wires being all of the same diameter and material, the lengths are in direct proportion to resistances.

37. Ascertain relation between Resistance and Weight. — Two copper wires of same length, and of known but different weights, being given to you, measure their relative resistances, and state relationship required.

38. Ascertain effect of Temperature on Resistance. — Accurately balance two copper wires in bridge; heat one of them, and note effect on needle. Shorten other wire, and so ascertain whether effect of heat was to diminish or increase the resistance, and by how much.

39. Experimentally establish the Laws of Divided Circuits.—Insert 1 foot of fine copper wire in one gap of bridge, in other gap insert (*a*) 2 feet of similar copper wire, (*b*) 2 feet of iron wire. Balance each against the copper standard; note ratios. Now put both the two lengths of copper and iron together and balance, once more noting ratio. From your measurements, show the truth of the formula, combined resistance $= \frac{G+S}{G \times S}$, where G equals the 2 feet copper wire, and S the iron wire.

40. Make a Rheochord.—Board 2 feet by 3 inches. Two uprights of wood 1 inch high, firmly let into board ½ inch from each end. Cut off 1 inch of glass tubing, having clear ½ inch internal diameter. Fit with small corks at each end, through which are bored two wire holes ¼ inch apart. Thread the ends of steel wire through corks, then fill tube with clean mercury. Strain the steel wire in two equal lengths across to each upright, the wires being parallel, ¼ inch apart, and about ⅜ inch above board. Connect one end of wire to a binding screw, the other to a mercury cup, ½ inch diameter and ½ inch deep, sunk in board. Measure the resistance of your whole wire, and make paper scale under wire, the scale being so divided as to indicate decimal parts of a unit.

41. Make a set of Resistance Coils.—Measure off (by bridge) lengths of silk-covered German silver wire, having resistances of 1, 2, 2, 5, 10, 20, 20 units. Wind each length of wire on a cork or cotton reel, and soak wire on it with melted paraffin. Make six more mercury cups, 1½ inch apart, like the one already made, in a row along one edge of board of your rheocord. Fasten the bobbins of wire along other edge in a row opposite interspaces between mercury cups. Lead one end of first coil of wire under board and up into first mercury cup, securing it below with a little shell-lac. Lead second end of first coil, and likewise first end of second coil, into second cup; second end of second coil, and first end of third coil, both into third cup, and so on. Make seven thick copper wire staples, 1½ inch long, and turned down ½ inch each end for connecting cups. Mark value of coil connected with each pair of mercury cups on board between them. Fill cups with mercury. Amalgamate loose copper connections. Note down temperature of room wherein coils were measured.

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